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PROPERTIES AND TESTING OF MAGNETIC MATERIALS

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OF
MAGNETIC MATERIALS

BY

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PREFACE

The chief purpose of this book is twofold:

1. To give a reasonably complete resumé of our present knowledge of the magnetic properties of commercial ferromagnetic materials.

2. To describe the various useful methods of test which are suitable for the commercial inspection of magnetic materials and for research investigations, together with a critical examination of their accuracy and limitations.

No space will be given to a discussion of magnetic theory or to the properties of paramagnetic or diamagnetic materials, since this book is primarily for the experimenter, student, or electrical designer who desires definite information for use in the solution of some specific magnetic problem. We shall also ignore certain peculiar and interesting magnetic phenomena, such, for instance, as the Hall effect, which, while they may be of the utmost importance in a solution of the ultimate nature of magnetism, do not at present have any material significance from the standpoint of the engineer. For those who wish to go into the subject of modern magnetic theory, we recommend the series of articles entitled "Theories of Magnetism," by Saul Dushman, in the *General Electric Review* for 1916, pp. 351, 666, 736, 818, 1083, and "Theories of Magnetism," *National Research Council Bulletin* 18, as being very complete reviews of the subject; also the brief article entitled "Magnetic Susceptibilities," by S. R. Williams in *Science* for Oct. 14, 1921, gives an idea of our present knowledge or lack of knowledge of fundamental magnetic phenomena. It is assumed that the reader has an elementary knowledge of magnetism such as is contained in the ordinary textbook of physics and that he is acquainted with Ewing's "Induction in Iron and Other Metals."

No attempt will be made to give credit to the original discoverer of any particular phenomena, nor to give references to the original article on any phase of the subject under discussion.

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Since this book is written primarily for English readers when possible we shall give references to English publications even though these references may not be as complete or authoritative as certain foreign ones. Such references as are given will be for the purpose of supplementing the text and to give credit or authority for data presented.

This book will not deal specifically with the problem of the design of the magnetic circuits of electrical apparatus, but the information here contained on magnetic properties should be available in one form or another to every designer of electrical machinery, and can be used directly by any competent designer in connection with his standard design formulas and methods. The choice of data and information here collected is the result of many years contact on the part of the author with the varied problems of a magnetic nature which arise in connection with the design and construction of all types of electrical apparatus. It is hoped that the information in this book will be sufficiently complete so that the novice, as well as the experienced designer, can make a suitable choice of material for any magnetic purpose which may present itself, and that he may make a satisfactory selection of tools for the determination of the magnetic properties of any ferromagnetic materials which may be offered to him for test.

Also, we are presenting a short summary of the complicated, but by no means insoluble, problem of iron losses in rotating machines. This discussion is of necessity brief, since the subject would make a book in itself.

Finally, we are including a brief introduction to the subject of magnetic analysis. This is a new field and offers a new tool for the investigation of the properties of materials. It is expected that some day it may become an important adjunct to the present methods of physical testing.

Many of the chapters of this book were originally published in the *Electric Journal.* I wish to take this opportunity of expressing my appreciation of the valuable assistance rendered by the editorial staff of the *Journal* and particularly by Mr. C. R. Riker. I wish also to acknowledge my debt to Mr. L. W. Chubb, whose inspiring influence was largely responsible for my interest in the subject of magnetism, and to Mr. T. D.

Yensen, with whom I have been closely associated for some years and on whose published work I have drawn largely in connection with certain portions of this book.

Thos. Spooner.

Edgewood, Pa.,
January, 1927.

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LIST OF IMPORTANT SYMBOLS

A = Cross-section of test specimen in cm^2.
a = Mean cross-section of exploring coil in cm^2.
α = Hardness factor where $\nu = \alpha + \sigma H$.
$\alpha = \sqrt{1 + \sin \tau}$ in Latour's formulas.
B = Flux density or induction in gausses or kilogausses.
B_d = Induction for demagnetization curve.
B_f = Ferric or intrinsic induction where $B_f = B - H = 4\pi J$.
B_m = Maximum normal induction.
B_m = Mean displacement of unsymmetrical hysteresis loop.
B_r = Normal residual induction.
B_s = Saturation value of ferric induction.
D = Demagnetizing coefficient based on $H = H' - DJ$.
D_B = Demagnetizing coefficient based on $H = H' - DB_f$.
d = Specific gravity or density.
E = Volts (r.m.s.).
e = Volts (instantaneous).
η = Steinmetz coefficient where $W_h = \eta B_m{}^x$.
$\mathfrak{F}$ = Magnetomotive force (m.m.f.) gilberts.
f = Frequency in cycles per second.
ϕ = Flux in lines or maxwells.
H = Magnetizing force in gilberts per centimeter.
H_c = Coercive force in gilberts per centimeter.
H_d = Negative values of H for demagnetization curve.
H_m = Maximum magnetizing force in gilberts per centimeter.
I = Amperes, r.m.s. for a.c.
J = Intensity of magnetization $= \dfrac{B_f}{4\pi}$.
J_s = Saturation value of intensity of magnetization $= \dfrac{B_s}{4\pi}$.
k = Eddy-current coefficient.
κ = Susceptibility $= \dfrac{J}{H} = \dfrac{\mu - 1}{4\pi} = \dfrac{\mu_f}{4\pi}$.
L = Inductance.
l = Length of magnetic circuit in centimeters.
M = Magnetic moment.
M_h = Mutual inductance in millihenries.
μ = Normal permeability.
μ_d = Differential permeability $= \dfrac{dB}{dH}$ (positive increments on normal induction curve).
μ_Δ = Incremental permeability $= \dfrac{B}{H}$ (reversed increments under any conditions).

μ_f = Ferric permeability $= \frac{B_f}{H}$.
μ_m = Maximum permeability.
μ_o = Initial permeability.
μ_r = Reversible permeability.
N = Total number of turns in a coil. $\frac{N}{l}$ is the number of turns per centimeter $= N_c$.
N_1 or N_P = Number of primary turns.
N_2 or N_S = Number of secondary turns.
ν = Reluctivity ($\nu = \alpha + \sigma H$) — oersted-centimeter $= \frac{H}{B}$.
ν_f = Ferric reluctivity ($\nu_f = \alpha_f + \sigma_f H$) $= \frac{H}{B_f}$.
$\mathcal{P}$ = Permeance $= \frac{1}{\mathcal{R}} = \frac{A}{l}$.
R = Resistance (ohms).
$\mathcal{R}$ = Reluctance $= \frac{l}{A} = \frac{1}{\mathcal{P}}$.
ρ = Resistivity (ohm-centimeter).
σ = Coefficient of magnetic saturation where $\nu = \alpha + \sigma H$ and $\frac{1}{\sigma} = B_s$; or more exactly $\nu_f = \alpha_f + \sigma_f H$, where $\frac{1}{\sigma_f} = B_s$.
t = Thickness of laminations in centimeters.
V = Volume in cm^3 or in^3.
W or W_t = Total loss in watts.
W_e = Eddy-current loss in watts.
W_h = Hysteresis loss in watts or in ergs per cubic centimeter per cycle.
$W^{10}/_h$ = Hysteresis loss for a maximum induction of 10 kilogausses.
$W^{10}/_{60}$ = Total loss in watts for a maximum induction of 10 kilogausses and 60 cycles. Similar symbols, such as $W^{15}/_{50}$, may be used.
X = Reactance $= 2\pi fL$.

PART I

MAGNETIC PROPERTIES

THE PROPERTIES AND TESTING OF MAGNETIC MATERIALS

CHAPTER I

INTRODUCTION

Nearly every piece of electrical apparatus has a magnetic circuit. The few exceptions, such as the electrostatic voltmeter, are of very minor importance. In high-frequency apparatus the magnetic circuit is often largely in air, but in general the magnetic flux is carried through most of its path by some ferromagnetic material. The apparatus is usually built around the magnetic circuit and its limitations are very often those resulting from the properties of the available ferromagnetic materials. It is desirable, therefore, for every builder or user of electrical apparatus to know something of the properties of those available magnetic materials, in order that he may understand the limitations and possibilities of such apparatus.

The three ferromagnetic elements are iron, nickel, and cobalt in the order of their importance. The cores of electrical apparatus generally contain either iron or some alloy of iron; silicon, nickel, and cobalt being the most common alloying elements. It is possible to make a ferromagnetic alloy without using any of the three ferromagnetic elements, as in the case of the Heusler alloys, but such materials are at present, at least, of no commercial importance, although of great theoretical interest.

No one knows why some materials are highly magnetic and others are feebly (para) magnetic or even diamagnetic. It is not even known whether the magnetic properties of a substance are a characteristic of the atomic nucleus, the arrangement of the electrons in the atom, or are due to some molecular arrangement. It is pretty well agreed, however, that there are ultimate magnetic particles which interact on each other. These particles have magnetic polarities which, in an unmagnetized material, are oriented at random. As soon as the substance is subjected to an external magnetic field, the particles tend to orient themselves in one direction; and when they are all completely oriented in the direction of the applied field, the material is said to be saturated. There also is assumed to be a certain amount of friction between the magnetic particles, which would account for the phenomena of hysteresis. Ewing has described very striking experiments, with small magnets arranged close together and free to turn, which show that such a theory will account qualitatively at least for the shape of the magnetization curve and hysteresis loop.

The Magnetic Circuit.—The amount of flux in a magnetic circuit is governed by a definite law similar to Ohm's law for the electric circuit; namely,

$$\phi = \frac{\mathfrak{F}}{\mathfrak{R}}, \tag{1}$$

where ϕ is the total flux in the magnetic circuit,

$\mathfrak{F}$ is the magnetomotive force (m.m.f.),

$\mathfrak{R}$ is the reluctance.

Figure 1 illustrates a very simple magnetic circuit. Consider that the ring is of nonmagnetic material, that it has a mean diameter D which is large with reference to the radial width of the ring, and that the winding is uniformly distributed. Under these conditions, ϕ is the total lines of flux induced by the current in the coil. ϕ is usually expressed in magnetic *lines* or *maxwells*. The m.m.f. $\mathfrak{F}$ in the c.g.s. system is given by

$$\mathfrak{F} = 4\pi NI, \tag{2}$$

where N is the total number of turns,

I is the current in c.g.s. units.

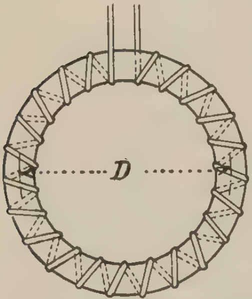

FIG. 1.—Simple magnetic circuit.

If I is in amperes,

$$\mathfrak{F} = 0.4\pi NI. \tag{3}$$

The unit of magnetomotive force is the *gilbert*. In the c.g.s. system $\mathfrak{R}$ is taken as unity for the reluctance of a centimeter cube of free space. This unit is called the *oersted*. In the case of the ring of Fig. 1, the reluctance in *oersteds* may be determined as follows:

$$\mathfrak{R} = \frac{l}{A}, \tag{4}$$

where l is the mean length of the flux path in centimeters.
A is the cross-section in square centimeters.
The reciprocal of the reluctance $\mathcal{R}$ is known as the *permeance* $\mathcal{P}$; namely,

$$\mathcal{P} = \frac{1}{\mathcal{R}}. \tag{5}$$

The field strength H in *gilberts per centimeter* is then,

$$H = \frac{0.4\pi NI}{l}. \tag{6}$$

Since l equals πD for the ring,

$$H = \frac{0.4NI}{D}. \tag{7}$$

The flux density B in *gausses* is

$$B = \frac{\phi}{A}, \tag{8}$$

and for air,

$$B = H. \tag{9}$$

These formulas apply equally well to the center of a long uniformly wound solenoid. For short solenoids, of course, the center portions will have a smaller field strength than given by these formulas.

Now, assume that the ring or core of Fig. 1 on which the winding is placed consists of a ferromagnetic material. This core will carry flux more readily than air or empty space. In other words, the reluctance $\mathcal{R}$ becomes less, and the flux for a given m.m.f. greater. Under these conditions,

$$\mathcal{R} = \frac{l}{\mu A}, \tag{10}$$

where μ is the *permeability* of the core material and is defined as

$$\mu = \frac{B}{H}. \tag{11}$$

If B is in gausses and H is in gilberts per centimeter, the permeability of air is then one. Some authorities prefer the use of other units for B and H, in which case the permeability of air may be different from one. The above definition of μ is probably preferable for scientific work, but for engineering and design calculations it is common to make the ampere-turn per centimeter or the ampere-turn per inch the unit of H, in which case the permeability of air would not be one.

For convenience, the reciprocal of the permeability is sometimes used; namely, the *reluctivity* ν.

$$\nu = \frac{1}{\mu}. \tag{12}$$

If a magnetic circuit consists of several portions in series having different reluctances, the total reluctance is the sum of the individual reluctances. If the magnetic circuit consists of several reluctances in parallel, the total reluctance may be found by adding the reciprocals of the reluctances and taking the reciprocal of the result. In the latter case the permeances $\mathcal{P}_1$, $\mathcal{P}_2$, etc., may be added directly to give the total permeance. This is exactly analogous to the case of the electric circuit for series and parallel resistances.

If the flux in the ring of Fig. 1 is caused to change, the instantaneous voltage will be:

$$e = 10^{-8}N\frac{d\phi}{dt}, \tag{13}$$

where e is in volts,
ϕ is in maxwells,
t is in seconds.

If the number of turns N is equal to one and the flux changes at the rate of 10^8 maxwells per second, 1 volt will be generated.

If a harmonically varying voltage is applied to the terminals of the coil, the relations are as follows:

$$E = \frac{4.44\phi Nf}{10^8} = \frac{4.44BANf}{10^8}, \tag{14}$$

where f is in cycles per second. This is probably the most useful and commonly used equation in electrical engineering.*

---

*For a much more complete discussion of the magnetic circuit relations, see Karapetoff's "The Magnetic Circuit;" or Pender's "Electricity and Magnetism for Engineers," Part I.

CHAPTER II

CHARACTERISTICS OF MAGNETIZATION AND PERMEABILITY CURVES

The nature of a magnetic material is most easily recognized from the characteristics of the normal magnetization or, as it is sometimes called, the *B-H* curve. Such a curve, Fig. 2, gives the relation between the normal induction *B* and the magnetizing force *H* and is obviously the locus of the tips of a series of hysteresis loops.

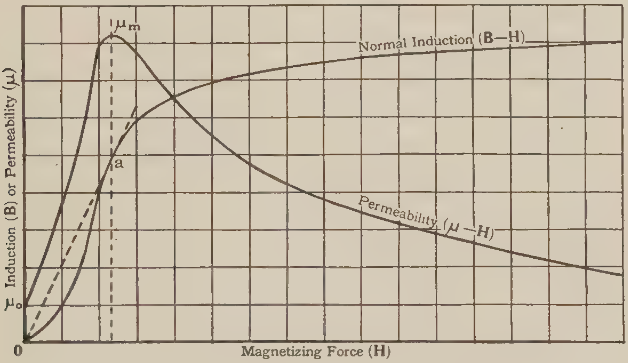

Fig. 2.—Typical magnetization and permeability curves.

Normal Induction.—As defined by the American Society for Testing Materials, normal induction is "the induction produced under a given magnetizing force in a substance which has been previously demagnetized and then subjected to a sufficient number of reversals of the given magnetizing force to bring it to a cyclic condition." In scientific literature and in countries using the metric system, it is usually expressed in lines per square centimeter (gausses). In England and in the United States the majority of the electrical designers prefer to express induction in lines per square inch. The relation between the various induction units commonly in use is given in Table I.

Magnetizing Force.—When the induction is expressed in gausses, the magnetizing force is usually given in gilberts per

TABLE I.—UNITS OF INDUCTION

	Maxwells (or lines) per square inch	Kilolines per square inch	Lines per square centimeter	Gausses	Kilo-lines per square centimeter	Kapp lines per square inch	Kapp lines per square centimeter
1 Line per square inch	1	0.001	0.155	0.155	0.000155	0.000167	0.0000258
1 Maxwell per square inch	1	0.001	0.155	0.155	0.000155	0.000167	0.0000258
1 Kiloline per square inch	1,000	1	155	155	0.155	0.167	0.02584
1 Kilomaxwell per square inch	1,000	1	155	155	0.155	0.167	0.02584
1 Line per square centimeter	6.45	0.00645	1	1	0.001	0.001075	0.000167
1 Maxwell per square centimeter	6.45	0.00645	1	1	0.001	0.001075	0.000167
1 Gauss	6.45	0.00645	1	1	0.001	0.001075	0.000167
1 Kiloline per square centimeter	6,450	6.45	1,000	1,000	1	1.075	0.1667
1 Kilomaxwell per square centimeter	6,400	6.45	1,000	1,000	1	1.075	0.1667
1 Kilogauss	6,450	6.45	1,000	1,000	1	1.075	0.1667
1 Kapp Line per square inch	6,000	6	930	930	0.93	1	0.155
1 Kapp Line per square centimeter	38,700	38.7	6,000	6,000	6	6.45	1

centimeter or in gausses. During the last few years there has been a strong tendency to use gausses in preference to gilberts per centimeter. Very recently, however, the tendency seems to be toward the use of the latter term. The discussion is too lengthy to be considered here, but the chief justification for the use of gausses as units of magnetizing force seems to be that, in air, the induction and magnetizing force are numerically equal in the c.g.s. electromagnetic system. Designers often use ampere-turns per centimeter. When the induction is expressed in lines per square inch, the magnetizing force is usually given in ampere-turns per inch. The relation between the units of magnetizing force are given in Table II.

TABLE II.—UNITS OF MAGNETIZING FORCE

	Gilbert per centimeter	Gausses	Ampere-turns per centimeter	Ampere-turns per inch
1 Gilbert per centimeter..	1	1	0.796	2.02
1 Gauss..................	1	1	0.796	2.02
1 Ampere-turn per centimeter...............	1.255	1.255	1	2.54
1 Ampere-turn per inch...	0.495	0.495	0.394	1

Ferric Induction.—By ferric induction is meant the increase in flux density over that produced in air by a given magnetizing force, due to the presence of such materials as iron, nickel, or cobalt, which are much more magnetizable than air. These materials are called ferromagnetic. Substances which are only slightly more magnetizable than air are called paramagnetic, and when slightly less magnetizable are called diamagnetic. The present discussion is concerned only with ferromagnetic materials, except as they may change into the paramagnetic or diamagnetic state due to thermal effects. The ferric induction is equal to $B - H$, where B is expressed in gausses and H in gilberts per centimeter. The ferric induction in gausses will be denoted by the symbol B_f.

Intensity of Magnetization.—The term *intensity of magnetization* is rarely used by engineers, but is common in scientific literature. It is equal to the ferric induction divided by 4π or,

$$J = \frac{B - H}{4\pi} \tag{15}$$

Saturation.—When all of the elementary magnetic particles become oriented in one direction, a material is said to be saturated. This means that no further increase of magnetizing force will increase the ferric induction, although, of course, the total induction B continues to increase by the same amount as the magnetizing force H. The saturation value of ferric induction will be known as B_s. Methods of calculating B_s from the constants of the magnetization curve at lower inductions will be given later.

Permeability.—The permeability of a material is a measure of the ease with which the elementary magnetic particles are oriented, and is numerically equal to $\frac{B}{H} = \mu$, when B is expressed in gausses and H in gilberts per centimeter. Fig. 2 gives a permeability curve plotted against H corresponding to the magnetization curve of the same figure. Often, in scientific literature susceptibility is used instead of permeability.

Susceptibility κ is related to the previously-defined properties as follows:

$$\kappa = \frac{J}{H} = \frac{\mu - 1}{4\pi} \tag{16}$$

It will be noted that while the permeability of air is one, the susceptibility of air is zero.

The *initial permeability* μ_o is that corresponding to zero H or zero B, and in ferromagnetic materials is usually of the order of several hundred.

The *maximum permeability* μ_m can most easily be obtained from the magnetization curve by drawing a tangent to the curve through O, as in Fig. 2. The maximum permeability is given by the slope of this line. The maximum permeability for most commercial ferromagnetic materials usually ranges from a few hundred to a few thousand.

The *differential permeability* μ_d for any point on the magnetization curve is equal to $\frac{dB}{dH}$ for that point, or is equal to the slope of the tangent to the magnetization curve drawn through the point. The maximum differential permeability is obtained by drawing a tangent to the magnetization curve at the point of inflection.

The term *reversible permeability*[1] applies only to very small changes of induction or magnetizing force. If, at any point on a magnetization curve or hysteresis loop, a small value of magnetizing force in the reverse direction is applied, there will be a corresponding small change of induction. The ratio of this change of induction to the change in magnetizing force is the reversible permeability μ_r. The reversible permeability is always less than the initial permeability.

By *incremental permeability*[2] μ_Δ, is meant the ratio of ΔB to ΔH for any position on a magnetization curve, or hysteresis loop, where ΔB and ΔH may be of any magnitude, but ΔH must be in the reverse direction from the immediately preceding change.

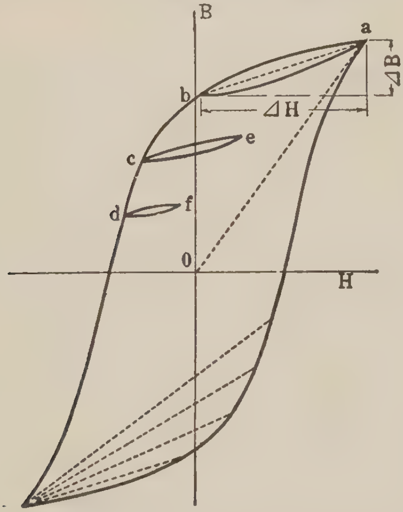

FIG. 3.—Typical hysteresis loop.

Showing minor loops and illustrating incremental permeability, $\mu\Delta = \frac{\Delta B}{\Delta H}$.

Reversible permeability is a special case of incremental permeability where ΔH is very small. Figure 3 shows the nature of this type of permeability; it is represented by the slope of the straight line drawn between the tips of a minor hysteresis loop. When the minor loops have one tip in common with a tip of the major loop, the incremental permeability is given by the dotted lines at the bottom of the major loop. This type of permeability is of importance when dealing with a magnetic circuit having both a direct and an alternating component of magnetization. This condition occurs in the teeth of induction motors, radio transformers, transformers supplying rectifiers, etc.

The term *effective permeability* is used to refer to the ratio of induction to magnetizing force for special conditions which are not otherwise defined. For instance, if a magnetic core is subjected to an alternating field of sufficiently high frequency, so that there is appreciable skin effect, such a term as *effective permeability* becomes useful. This expression may be used if desired instead of *incremental permeability.*

Extrapolation of Magnetization Curve.—In order to extrapolate magnetization curves and to obtain saturation values from data taken at moderate magnetizing forces, use is made of Frölich's law which states that the "permeability is proportional to the magnetizability." Expressed mathematically this becomes:

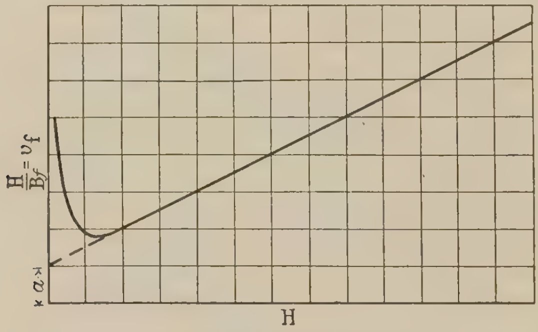

Fig. 4.—Reluctivity curve.

$$B = \frac{H}{\alpha + \sigma H}. \tag{17}$$

Kennelly[3] modified this law by introducing the reluctivity (ν), which is the reciprocal of the permeability:

$$\nu = \frac{1}{\mu} = \frac{H}{B}. \tag{18}$$

From equation (17)

$$\nu = \alpha + \sigma H. \tag{19}$$

If a series of values are taken from a magnetization curve and ν is plotted against H, a curve similar to Fig. 4 results, where α is given by the intercept on the vertical axis and σ is the slope of the right-hand portion of the curve. α may be considered the hardness factor of the material, since in general the harder the specimen magnetically the greater the value of α. σ is called the coefficient of magnetic saturation because it is from its reciprocal that the saturation is determined. When dealing with saturation values and high flux densities, it is necessary to use the ferric induction B_f. Equation (18) then becomes $\nu_f = \frac{H}{B_f}$. The saturation value of the ferric induction is then:

$$B_s = \frac{1}{\sigma_f} \tag{20}$$

and the induction for any magnetizing force over the straight portion of the reluctivity curve is calculated thus:

$$B = \frac{H}{\alpha_f + \sigma_f H} + H. \tag{21}$$

Referring again to Fig. 4, the straight portion of the curve may begin at a magnetizing force of 50 gilberts per centimeter, or more often not until 200 is reached. For most commercial materials, a satisfactory extrapolation may be made from points at 200 and 400 gilberts per centimeter.[4,5] For certain special alloys, such as some cobalt steels, much higher magnetizing forces are necessary before the saturation values can be accurately estimated, since the reluctivity curve shows a bend at several hundred gilberts per cm. Such a bend has a special significance, as will be pointed out later.

Effect of A.C. on Magnetizing Curve.—If an alternating field is applied to a magnetic core, and then an attempt made to obtain a magnetization curve by means of a permeameter or some ballistic method, it will be found that for moderate inductions and alternating magnetizing forces the apparent permeability will be increased. Figure 5 shows a set of such curves obtained on ring samples.[6] This material was very thin high-silicon steel. The alternating flux was supplied by applying 60-cycle current to a winding surrounding the sample. The d.c. magnetization curves were then obtained by means of two other windings in the usual way. The B_{dc} values correspond to the mean change in flux caused by reversing the current in the d.c. magnetizing winding. The H values are those calculated from this current. B_m is one-half the total alternating-flux amplitude as calculated from the induced alternating voltage. The apparent effect of applying alternating flux is to make the elementary magnetic particles orient themselves more readily for low and moderate inductions.

If the maximum permeability and the corresponding value of H are determined from these curves, as in Table III, some interesting points are brought out more clearly.

TABLE III.—MAXIMUM PERMEABILITIES

B_m	0	1	2	3	5	8	10	12
μ_m	1200	2650	3800	4000	3400	2200	1100	550
H for μ_m	5.5	1.3	0.7	0.5	0.8	0.8	1.1	1.5

It will be seen that the apparent maximum permeability reaches a maximum as the alternating flux increases, and then decreases. Niwa and Asami have calculated the reluctivity curves corresponding to the magnetization curves of Fig. 5, some of which are reproduced in Fig. 6. The variations of the intercepts α and the slopes σ with B_m are shown by the insert. The magnetic hardness α reaches a minimum at about B_m equals 3 kilogausses, but the slope σ increases continuously with B_m. This means that, as B_m increases, the apparent saturation decreases. It should be noted that for large values of B_m there is still a departure from a straight line near the origin, although it is much less than for zero B_m.

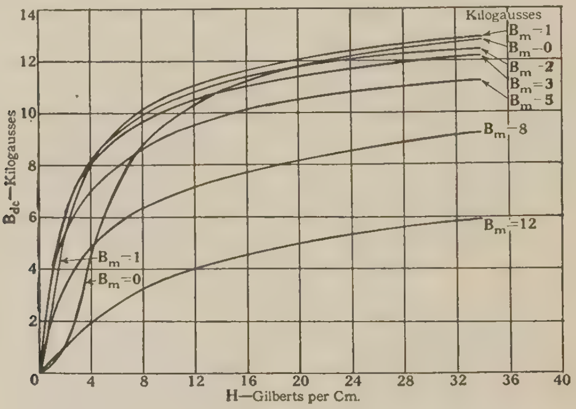

FIG. 5.—Magnetization curves under superposed alternating fields.

Magnetization curves of the type described above are often called anhysteretic curves. The hysteresis can be suppressed to a considerable extent by means of mechanical vibrations or apparently almost completely by means of an alternating flux. If an alternating flux is used, moreover, it may be applied in the same direction as the d.c. flux or it may be applied at right angles. Some of the best work on this subject has been done by passing a.c. longitudinally through the sample under test in the same direction as the d.c. flux. This would, of course, produce an alternating field at right angles to the direct field. As pointed out by Wright[7] if the alternating flux is present at the same time as the d.c. flux, certain distortions will result. It is better to avoid this by using the method of Steinhaus and Gumlich[8] which consisted in gradually reducing the alternating flux to zero before observing the resulting magnetization. Ashworth[9] has published some interesting results along this line. He did not, however, take the precaution to reduce his alternating flux to zero before observing the direct flux. Figure 7 shows some typical results. J is the intensity of magnetization; H is the d.c. magnetomotive force; and i_a is the a.c. passing through the sample. The dotted curves at the left of Fig. 7 are the results when the a.c. is reduced. The reciprocal of the intensity of magnetization when plotted against the a.c. gives practically straight lines as shown. Ashworth has expressed these results by the following equation:

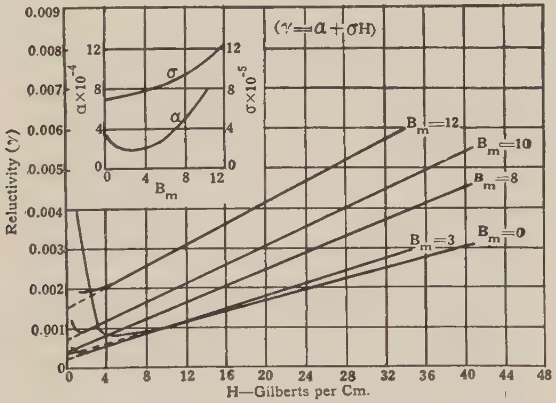

FIG. 6.—Reluctivity curves under superposed alternating fields.

$$H\left(\frac{1}{J} - \frac{1}{J_o}\right) = C(i_a + b) \tag{22}$$

where J_o is the limiting intensity of magnetization for this sample of iron in the field employed and equals 1177, $C = 1.8 \times 10^3$ and $b = 1.1$.

In the case of the alternating flux parallel to the direct flux, curves similar to those of Fig. 7 are obtained, where the alternating flux is at right angles to the direct flux. Niwa and Asami have shown such curves. The explanation of these effects is simple, but can best be given in connection with the consideration of displaced hysteresis loops as discussed later. It is evident that where the two fluxes are parallel incremental permeabilities must be dealt with. If the laws of incremental permeability and the constants for any given material are known, the shape of the anhysteretic curves can be predicted. In the case where the fluxes are at right angles, the shape can be predicted only qualitatively. As will be pointed out later, the hysteresis is not really suppressed, the effects being only apparent. The hysteresis is actually supplied from the a.-c. circuit instead of the d.c., thus giving the apparent suppression, as judged from the d.-c. measurements.

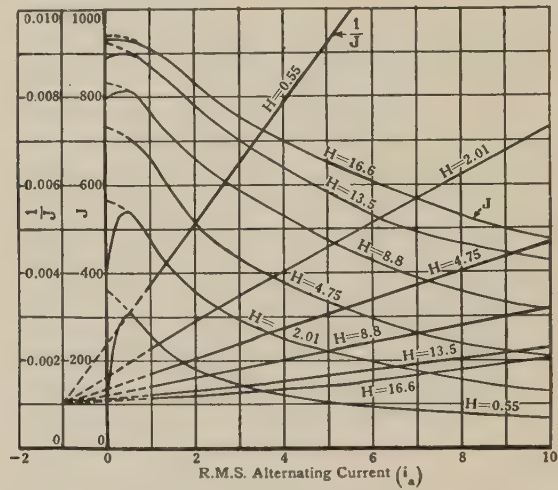

FIG. 7.—Effect of a.-c. on d.-c. magnetization curves.

For 0.057-centimeter diameter iron wire. A.-c. frequency = 33 cycles per second. One ampere of a.c. is equivalent to a magnetizing force of 9 gilberts per centimeter at the circumference of the wire.

Nickel gives similar results to those obtained with iron, but it is much more difficult to suppress the hysteresis, due probably to the fact that the nickel has a much higher coercive force.

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CHAPTER III

NORMAL HYSTERESIS AND EDDY-CURRENT LOSSES

HYSTERESIS

A normal hysteresis loop* and the normal induction curve corresponding to it are shown in Fig. 8. For a short distance at the higher inductions it will be noted that the magnetization curve lies outside of the loop. This is more often the case than not, although text books generally show the curve well inside of the loop. Apparently, no satisfactory explanation of this effect has been published, although several have been suggested.

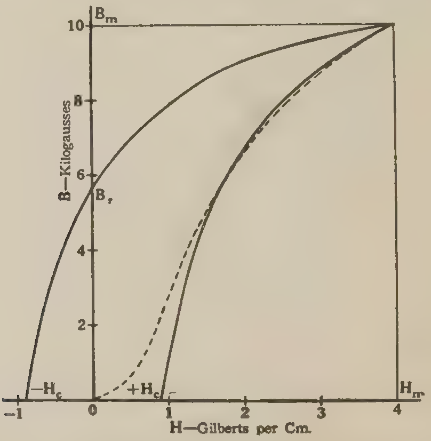

Fig. 8.—Normal hysteresis loop and magnetization curve.

Characteristics.—There are several characteristics of the hysteresis loop which are of use in classifying magnetic materials. These characteristics in general vary with the maximum induction B_m according to some more or less definite law.

The residual induction or retentivity B_r is the induction in the material when the magnetizing force has been reduced to zero.

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* Only normal or symmetrical hysteresis loops will be considered in this chapter. A later chapter will be devoted to a discussion of unsymmetrical or displaced hysteresis loops.

This means that not only shall there be no external magnetizing force, but that also there shall be no demagnetizing force due to variations in the magnetic circuit. These conditions can be met by a ring sample of homogeneous material and uniform cross-section.

The coercive force H_c is the negative or demagnetizing force necessary to bring the induction in the material to zero. This factor is closely associated with the hysteresis loss, since it chiefly determines the width of the loop. It is of very great importance in permanent-magnet steel, since it determines largely the effectiveness of the demagnetizing forces and therefore the stability of the material under external magnetic influences. For electrical sheet it is desirable to have the coercive force as small as possible, and for permanent-magnet steel as large as possible.

The hysteresis loss is proportional to the area of the hysteresis loop. When the induction is plotted in gausses and the magnetizing force in gilberts per centimeter, the hysteresis loss is equal to

$$W_h = \frac{KA}{4\pi}, \tag{23}$$

where W_h is the hysteresis loss in ergs per cubic centimeter per cycle, K is a constant and is numerically equal to the product of the gausses per unit of ordinate and the gilberts per centimeter per unit of abscissæ, and A is the area of the loop expressed in the same units. For instance, if 1 centimeter of ordinate corresponds to 2000 gausses, and 1 centimeter of abscissæ to 5 gilberts per centimeter and the area of the loop as obtained by planimeter or some other convenient means is 20 square centimeters the loss will be:

$$W_h = \frac{2000 \times 5 \times 20}{4\pi} = 15{,}900 \text{ ergs per cubic centimeter per cycle} \tag{24}$$

If it is desired to convert this to watts per kilogram for some definite frequency f multiply as follows:

$$W_h \times \frac{10^{-4}f}{d} \text{ watts per kilogram}, \tag{25}$$

where f is the frequency in cycles per second, and d is the density.

In evaluating a material for use in permanent magnets, the chief interest is the demagnetization curve between B_r and H_c.

In addition to the characteristics already mentioned, it is considered by many investigators and designers, especially in Germany, that the product of B_r and H_c is of prime importance in determining the value of a magnet steel. In England great importance is given to the maximum value of the product of B and H for the demagnetization curve. A curve showing the product of these two factors is given in Fig. 9. This product may be called B_dH_d and the shape of the B_dH_d curve gives the available magnetic energy for different designs.

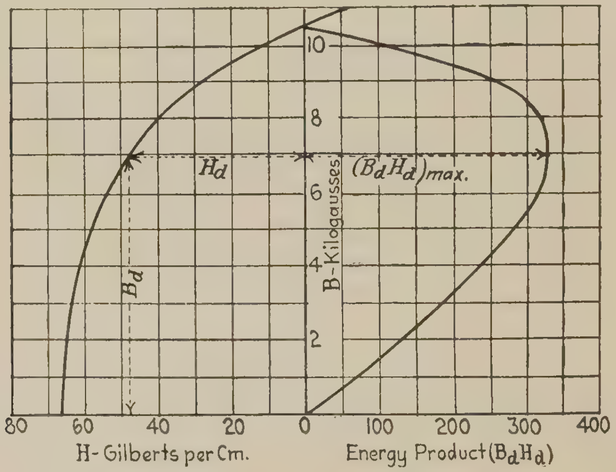

FIG. 9.—Demagnetization curve and energy product for permanent-magnet steel.

Saturation Effects.—Sanford and Cheney[1] of the Bureau of Standards have shown that B_r and H_c follow a law similar to Frohlich's for induction and therefore have definite limiting values. B_r and H_c values may be extrapolated by the following equations: (see Fig. 10 and 11 for typical curves):

$$\frac{H_m}{B_r} = a_1 + b_1H_m, \tag{26}$$

$$\frac{H_m}{H_c} = a_2 + b_2H_m, \tag{27}$$

where H_m = maximum magnetizing force; B_r = residual induction; H_c = coercive force; a_1 and a_2 = the intercepts on the axis of ordinates when the left-hand members of the equations are plotted against H_m, and b_1 and b_2 are the slopes of the lines.

The reciprocal of b_1 gives the saturation value of B_r, and the reciprocal of b_2 gives the saturation value of H_c.

Relation between H_c and Loss.—As pointed out above there is an intimate relation between H_c and the hysteresis loss.

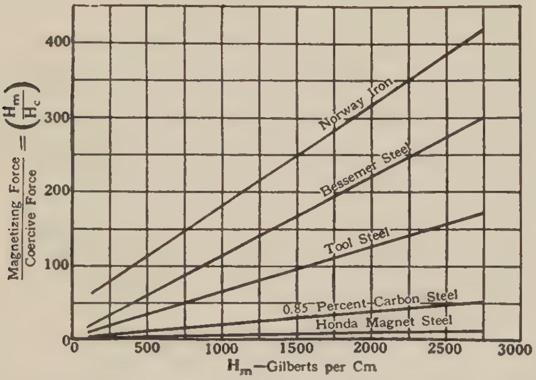

FIG. 10.—The relation between $\frac{H_m}{H_c}$ and H_m for a number of materials.

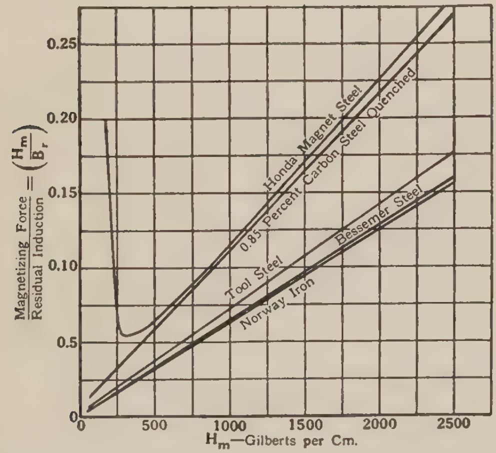

FIG. 11.—The relation between $\frac{H_m}{B_r}$ and H_m for a number of materials.

When the induction is given in gausses and the magnetizing force in gilberts per centimeter the hysteresis loss is roughly the following:

$$W_h = \frac{B_m H_c}{\pi} \text{ ergs per cubic centimeter per cycle} \qquad (28)$$

This is said to give results which are within 15 per cent plus or minus of being correct,* but it is believed that sometimes the error may be considerably greater than this.

Anderson and Lance[2] have recently shown that the following simple relation holds:

$$W_h = aB_mH_c \tag{29}$$

where $a = 0.2133 + 0.01082 \times 10^{-3} \times B_m$. This seems to give approximately correct results in most cases provided the inductions are not taken higher than 15 kilogausses.

Gumlich[3] has shown that where higher inductions are involved the constant a can be expressed more accurately thus:

$$a = (0.225 + 0.000889 \times 10^{-3} \times B_m) + (0.000861 \times 10^{-6} \times B_m^2).$$

This function may be plotted in the form of a curve between a and B_m as given in the original article, and this gives a simple and useful relationship for obtaining W_h from the H_c value, or H_c from the loss. The same article gives a simple method of estimating the maximum permeability from the B_r and the H_c values, and also the corresponding induction.

For hysteresis loops having a maximum induction of 10 kilogausses, a more accurate method of estimating the loss from the characteristics of the loop without using a planimeter is the following:[4]

$$W_h = \frac{2(H_8'' - H_8')}{2H_c + (H_8'' - H_8')} \times \frac{H_c \times 10^4}{\pi} \text{ ergs per cubic centimeter per cycle,} \tag{30}$$

where H_8' and H_8'' are the two values of H corresponding to an induction of 8 kilogausses. H_8'' is the numerically larger value. The accuracy is usually better than plus or minus 5 per cent. In order to convert to watts, multiply by the frequency and divide by 10^4 times the density of the material.

As has been pointed out very clearly by Ball[5] and Gumlich, there is one condition under which the ordinary relation between hysteresis loss and coercive force many not hold. It is the case where there are a low and a high coercive-force material in parallel. This is illustrated by Fig. 12. It is evident that when the mean induction is reduced to zero it may have a fairly high positive value in the high coercive-force material and a large negative value in the low coercive-force material. If the cross-section of the two materials is nearly equal, the apparent coercive force will be slightly higher than that of the low coercive-force material. This gives a very much distorted hysteresis loop which is much narrower than usual in the region of zero induction.

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* See *Bur. of Standards Circular* 17.

Such a condition as this may arise in commercial material under certain conditions. For instance, in the case of a bar of high-carbon steel, of which the carbon content is decreased near the surface by some heat-treatment process, there will result a hysteresis loop with an abnormally low coercive force. A case-hardened sample will show the same thing magnetically, but in this case the high-carbon material is on the surface. These effects are important in connection with certain problems in magnetic analysis.

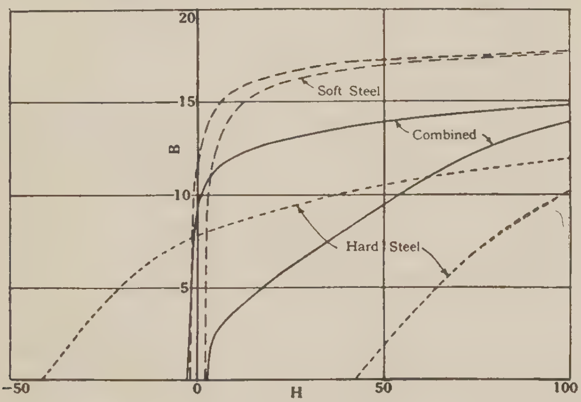

FIG. 12.—Effect of combining high- and low-hysteresis material.

Steinmetz' Law.—This law,

$$W_h = \eta B_m^x \tag{31}$$

connecting induction and hysteresis loss, is an empirical relation, which can be used to advantage if its limitations are recognized. The coefficient η is proportional to the area of the hysteresis loop, and is dependent on the material, heat-treatment, physical condition, etc. The mean value of the exponent x as given by Steinmetz is 1.6. This varies somewhat for different magnetic materials, but holds approximately for a range of inductions from about 1 kilogauss to perhaps 12 kilogausses. For very low inductions, the hysteresis loss varies approximately as the square of the induction. For inductions above 12 kilogausses, the exponential law does not hold for commercial magnetic materials, but the loss increases at a higher rate, this rate becoming greater the higher the induction. Figure 13 shows a hysteresis-loss curve for a sample of electrical sheet with the logarithm of the induction plotted against the logarithm of the loss. The slope of this curve, of course, gives the apparent exponent. For the region where the line is curved, the slope is called the ratio of variation. This slope, under certain circumstances, may be as high as four or five.* It is believed by some[5] that, if a material were perfectly homogeneous, the exponent 1.6 would hold for the highest inductions. It is true, of course, that if two materials of different permeability and with different hysteresis coefficients have parallel flux paths the resultant ratio of variation will have a higher value than the exponents of the individual components.

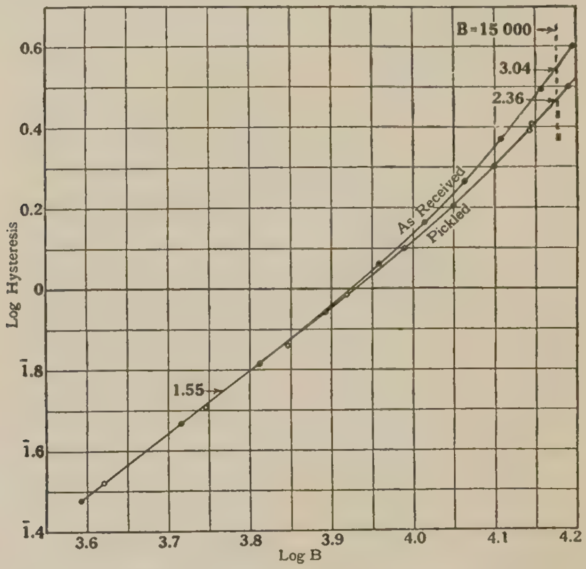

FIG. 13.—Logarithmic curves for 4 per cent silicon sheet steel. Showing apparent exponent and effect of removing scale.

This is well illustrated by the case of the heavy scale which usually is present on the surface of high silicon electrical sheet.

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* For a discussion of the relation between exponent and ratio of variation, see the *Bur. of Standards Circular* 17, on Magnetic Testing.

Ball[5] has shown that this scale has a very low permeability as compared with the steel, and that it has a very high hysteresis coefficient. At moderate inductions there is practically no flux in the scale and therefore no appreciable loss due to it. At high inductions the scale begins to carry flux and due to its high specific loss the total hysteresis loss for the sample increases very rapidly with the induction. This means a high ratio of variation. As shown by Fig. 13, if the scale is removed by picking, the ratio of variation at high inductions is considerably decreased. It will be noted, however, that the removal of the scale does not produce a constant exponent for the material, although the double-log curve is considerably straightened out.

In some cases the double-log curves are curved over the whole range of inductions. Under these circumstances the relation between the loss and the induction often can be expressed best by the following formula:

$$W_h = aB + bB^2 \tag{32}$$

Obviously, this will not hold for very high inductions where the loss increases faster than the square of the induction. It has the advantage over the Steinmetz equation that it does not require the use of logarithms for its solution. Also, it often can be applied over a wider range of inductions than the Steinmetz law.

EDDY CURRENTS

Whenever the flux in a magnetic material alternates or varies, eddy-current, or foucault-current losses, as well as hysteresis losses, are present. In electrical machinery these eddy-currents are often responsible for 50 per cent or more of the core losses, and in the design of electrical apparatus deserve more attention than is given them. Unless the frequency is sufficiently high to produce skin effect, the hysteresis loss per cycle is independent of the frequency, *i.e.*, the total hysteresis loss is directly proportional to the frequency. The eddy-current loss per cycle, however, is directly proportional to the frequency. The total eddy loss, therefore, is proportional to the square of the frequency. Then for sheet material,

$$W_e = kf^2B^2t^2 \tag{33}$$

where W_e is the eddy-current loss per unit volume or weight; k is a constant depending on the resistivity of the material and some other factors to be discussed later; f is the frequency; B is the induction; and t is the thickness of the sheet. From theoretical considerations it can be shown that the eddy-current loss for sheet material, when skin effect is negligible,[6] is

$$W_e = \frac{\pi^2 t^2 f^2 B^2}{6\rho \times 10^{16}} \tag{34}$$

where W_e is in watts per cubic centimeter; t is in centimeters; f is in cycles per second; B is in gausses; and ρ is in ohm-centimeters.

It will be found that, in general, the eddy losses as calculated by this formula are too low as compared with actual test values. This is especially true for silicon steel. It has been shown by Ruder[7] that the larger the grain size the greater the eddy loss up to the point where the grains become as thick as the sheet. Conversely, the thinner the sheet the greater the eddy loss as compared with the theoretical loss for the same thickness of sheet. The reason why this discrepancy is so great for silicon steel is that the grain size for this class of material is especially large. Table IV gives some data showing these effects.

TABLE IV

Material	Gage, inches	Eddy-current loss			Resistivity, ohms
		Test	Calculated	Per cent excess	
Bessemer	0.028	1.115	0.777	56.4	14×10^{-6}
Bessemer	0.065	5.25	4.18	25.6	14×10^{-6}
Bessemer	0.131	13.5	16.95	−20.3	14×10^{-6}
1 per cent silicon	0.018	0.296	0.195	51.9	23×10^{-6}
2.2 per cent silicon	0.015	0.127	0.0864	47.0	47×10^{-6}
2.2 per cent silicon	0.034	0.702	0.444	58.2	47×10^{-6}
2.2 per cent silicon	0.076	2.88	2.22	29.7	47×10^{-6}
4 per cent silicon	0.015	0.140	0.0581	141.0	60×10^{-6}

These losses are expressed in watts per cycle per cycle per kilogram × 10^3. The maximum induction was 10 kilogausses, and the frequency 60 cycles. These test results were obtained on ring samples having a mean diameter of 3 inches and a radial width of 0.5 inch. The punchings were not annealed after stamping and therefore the losses are slightly different than would otherwise be the case. Data on annealed samples would have been better, but were not available in the form desired. The hysteresis and eddy losses were separated by testing at 30 and 60 cycles in the usual way. The results were checked against ballistic hysteresis loops.

It will be noted that while high resistance means decreased eddy losses, nevertheless, due to other factors which accompany the high resistance, the eddy losses are not inversely proportional to the resistivity. This is contrary to the usual textbook statement. Also, the losses are not inversely proportional to the square of the thickness of the sheets, but decrease less rapidly than the square law with decreasing thickness.

Unless the laminations are effectively insulated from each other, the eddy-current losses may be much greater than would be otherwise the case. The scale which is formed on the surface of sheets during the process of manufacture is a much poorer electrical conductor than the steel itself, but still is a fairly good conductor. When the pressure between laminations is low, as in certain small transformers, this scale is sufficient insulation. In most apparatus, however, additional insulation is required. It is the general practice in America to coat the laminations, either before or after punching, with some kind of enamel. This is usually baked on, but an air-drying varnish is sometimes used. If the steel is to be annealed after punching, of course, the enamel must be applied after the punching operation. In Europe it is common practice to apply a coat of paper to one side of the sheet before punching. This perhaps makes a slightly more uniform and reliable insulation than the enamel, but it precludes the possibility of annealing after punching and, what is more important for apparatus which is to operate at high inductions, the paper occupies more space than the enamel, thus producing higher net inductions in the steel, and hence larger losses and magnetizing current.

By decreasing the thickness of the laminations, the eddy losses can be reduced to any desired extent. There is a limit, however, beyond which it does not pay to go, depending on the frequency. If the material is made too thin, the space occupied by the insulation becomes excessive, thus increasing the net induction, as mentioned above when considering paper insulation. Since the losses go up approximately as the square of the induction, and the exciting current at a much greater rate, at high inductions the space required for the insulation must be kept at a minimum.

Again, thin material costs more to manufacture than thick, and much more to punch and assemble. Finally, unless very special heat-treatment is used, thin sheets have a higher hysteresis loss per unit weight than thick sheets. This is probably connected in some way with the fact that thin material has a finer grain structure than thick material, and it is known that, other things being equal, the smaller the grains the higher the hysteresis loss. If the eddy loss is greater than the hysteresis loss, of course, the smaller grain size may be an advantage.

It has been learned that the best balance between these various factors is found by using sheets having a thickness of from 12 to 28 mils for the cores of transformers and rotating apparatus which are to be operated on commercial frequencies. 14-mil sheet is perhaps the most common in America. For the poles of salient-pole machines and for certain special cases thicker material often may be used to advantage. For radio-frequency apparatus, sheet from 1 to 3 mils thick is most commonly used. Aside from the cost of manufacture, it does not pay to go much below 1 mil in thickness, due to the insulation space required. It is difficult to roll high-silicon steel to less than 2 mils.

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CHAPTER IV

RANGE OF PERMEABILITY AND CORE-LOSS VALUES

This chapter will be devoted to a consideration of the permeability and core-loss characteristics of commercial and semicommercial magnetic materials. At the same time the importance of these various materials from a magnetic standpoint will be brought out and an attempt made to show how their specific characteristics may be best utilized.

Pure Iron.—The purest iron (except electrolytic iron), which is commercially available in large quantities is American ingot iron. It is obtainable in the form of rods, wire, sheet, or in almost any shape which may be desired. This material is carefully degasified and has the following approximate composition:

C	0.011 per cent
S	0.032 per cent
P	0.008 per cent
Mn	0.017 per cent
Si	trace
Cu	0.03 per cent
O	0.025 per cent

For suitably heat-treated material, the initial permeability is about 250 and the maximum permeability, which occurs at about 6000 gausses, is from 6000 to 8000. Unless the iron is carefully annealed, the maximum permeability will be much less than this. The saturation value B_s is about 21,600 gausses, which is the highest obtainable for any known magnetic material with the single exception of an iron-cobalt alloy to be discussed later. The hysteresis loss for annealed sheet is about 0.025 watt-second per cycle per kilogram.* (To convert to ergs per cycle per cubic centimeter, multiply by the density and by 10^4.) Due to its low resistivity (about 10 microhm-centimeters) the eddy-current losses are high. They may be calculated approximately by formula (34) with a small addition depending on the grain size and thickness of material, provided the skin effect is negligible. Ingot iron has a very limited use for magnetic purposes since, in general, it cannot be used under a.-c. conditions, due to its low resistivity and therefore high eddy losses. Where cores for d.-c. apparatus are required, the material is quite satisfactory, due to its high saturation value and comparatively low coercive force. The latter characteristic results in low effective residual if there is an air-gap in the magnetic circuit.

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* Unless otherwise specified, the hysteresis-loss values as given in this chapter will correspond to an induction of 10 kilogausses as calculated from the weight of the material and an assumed density of 7.7 for low-silicon steel and 7.5 for high-silicon steel. For other materials, such as nickel and cobalt alloys, the densities corresponding to the actual tested values are used.

If pure iron with better magnetic characteristics than ingot iron is desired, vacuum-fused electrolytic iron may be used. The remarkable properties of this material will be considered in a later paragraph.

Cast Iron.—In the earlier days of electrical machinery, cast iron was used to a considerable extent for the yokes and frames of electrical apparatus. In modern machines it is less often found. The maximum permeability is about 500 at an induction of from 2 to 5 kilogausses. For such a variable material as cast iron only rough approximations can be given for the magnetic properties of the material as it is customarily used in electrical apparatus. The saturation value B_s is about 14 kilogausses. The resistivity is of the order of 100 microhm-centimeters. From a magnetic standpoint cast iron is a very poor material, but it is used because of its cheapness, ease of casting, and machinability. Malleable cast iron has magnetic properties about midway between cast iron and cast steel. A magnetization curve for cast iron is shown in Fig. 14.

Cast Steel.—Magnetically, this material is much superior to cast iron. It has a maximum permeability of about 1500 at an induction of about 7 kilogausses. Its saturation value of about 21 kilogausses is not much lower than that for pure iron. It is used very considerably for the yokes and frames of rotating machines. As for cast iron, the magnetic properties vary considerably with chemical composition and heat-treatment. The resistivity is about 15 microhm-centimeters. A magnetization curve for cast steel is shown in Fig. 14.

Bessemer Steel.—This class of material is seldom used in electrical apparatus, except for laminated poles where it finds a considerable application due to its cheapness. It has a maximum permeability of about 1900 at an induction of 9 kilogausses. It is seldom used in thickness of less than 0.0281 inches (0.071 centimeter). As obtained from the manufacturer, 0.0281-inch-thick material has a hysteresis loss of about 0.10 watt-second per cycle per kilogram, and a resistivity of about 14 microhm-centimeters. The eddy-current losses for several thicknesses of sheet are given in Table IV.* A typical magnetization curve is given in Fig. 14.

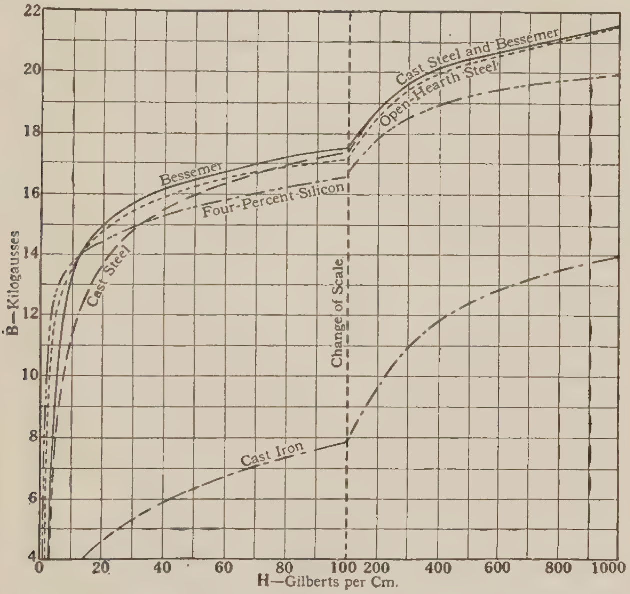

FIG. 14.—Magnetization curves for commercial magnetic materials.

Open-hearth Steel.—In the form of sheet steel, this material is used very largely for the cores of transformers and particularly of rotating machines. It is often known as electrical, or dynamo, sheet and appears in various grades and under different trade names, the grades depending on the care in manufacture and the silicon content. Under this head only steel having a silicon content of 1 per cent or less will be included. As received from the manufacturer in the mill-annealed condition, it will have a maximum permeability at about 6 kilogausses of from 3000 to 6000. By suitable re-annealing, the maximum permeability may be increased to between 4000 and 8000. The saturation values will vary from 20 to 21 kilogausses, depending chiefly on the silicon content, thickness of sheets, and amount of scale. Other things being equal the higher the silicon content the lower the saturation induction, since the silicon acts as a diluent. It should be understood that the saturation induction is based on the net section of the iron as determined from the weight and an assumed density of 7.7. In the form of plates or heavy sheets, this material will have a considerably lower maximum permeability unless it has been specially heat-treated. The saturation values usually will be a little higher. Figure 14 gives a magnetization curve for a medium grade electrical sheet.

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* See previous chapter.

The hysteresis loss for this kind of material varies considerably with the chemical composition and care in manufacture. For mill-annealed material 0.0172 inch thick, it will vary from 0.03 to 0.04 watt-second per cycle per kilogram. The eddy-current losses are a function chiefly of the resistivity and thickness of the sheets.* The resistivity of iron is increased slightly more than 10 microhm-centimeters for each per cent increase in silicon content. Since the resistivity of pure iron is about 10 microhm-centimeters, the addition of 1 per cent of silicon, other things being equal, will reduce the eddy losses to about one-half.

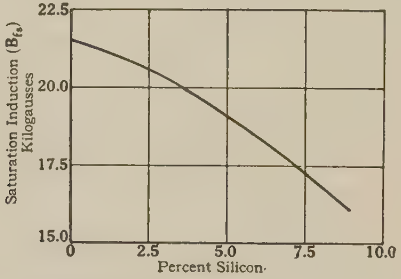

Fig. 15.—Saturation induction of iron-silicon alloys.

Silicon Steel.—This material in the form of electrical sheet is divided into two general grades depending on the silicon content; medium-silicon steel with a silicon content of from 2 to 3 per cent and high-silicon steel with a silicon content of from 3.5 to 4.5 per cent. The saturation induction for silicon steel decreases with silicon content. The magnitude of this effect is shown by Fig. 15.†

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* As pointed out in Eq. (34).

† According to data reported by Gumlich. Yensen has reported somewhat higher values for purer alloys but qualitatively the results are the same. Probably Yensen's results are slightly high.

Medium-silicon steel is used in motors and generators to a considerable extent and also in transformers. It has a slightly higher maximum permeability than ordinary open-hearth steel, but a slightly lower permeability at high inductions than the steel with the lower silicon content. It finds its chief application in apparatus which operates at moderate inductions and where it is desired that the hysteresis and eddy-current losses shall not be too high. Its thickness is usually from 14 to 28 mils (0.036 to 0.072 centimeter). The hysteresis loss for mill-annealed

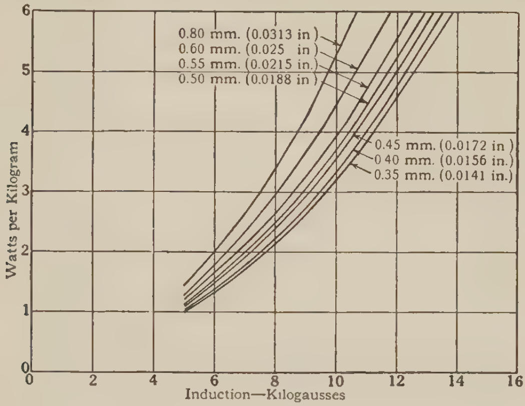

FIG. 16.—Total core loss for low-silicon steel at 60 cycles per second.*

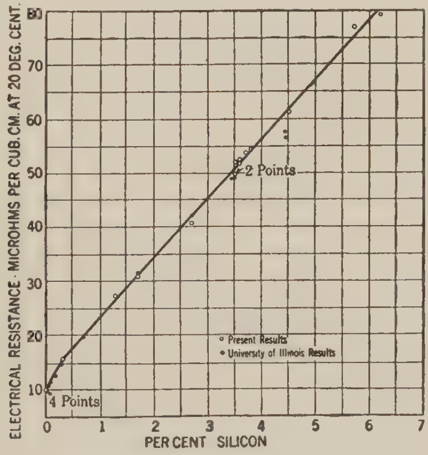

FIG. 17.—Electrical resistance of iron-silicon alloys.

* Figures 16, 18 and 19, are due to American Sheet and Tin Plate Co.

material, 0.014 inch thick, is from 0.025 to 0.03 watt-second per cycle per kilogram. The saturation value is about 20.3 kilogausses. For solid material, steel with this silicon content would have a saturation value somewhat higher. The resistivity of steel with various silicon contents is given by Fig. 17. The total 60-cycle loss for medium-silicon steel is given by Fig. 18. The magnetization curve lies between those for open-hearth steel and 4 per cent silicon.

High-silicon Steel.—In the manufacture of this grade of steel great pains are taken to keep the impurities very low, since this is essential to low hysteresis loss. Except for the silicon content, the composition is much like that of ingot iron as given in a previous paragraph. It is especially desirable to keep the carbon and sulphur low. A few thousandths of 1 per cent change in the carbon content will appreciably affect the hysteresis loss. This material is the best grade of electrical sheet obtainable on the market and is relatively expensive. Its chief application is in 60-cycle transformers where it is desired that the iron losses shall be as low as possible. It is impossible to carry the silicon content much over 4.5 per cent without encountering mechanical difficulties due to brittleness. It has a maximum permeability ranging from 5000 to 10,000 at inductions from 6 to 8 kilogausses. Its saturation value is rather low, however, due to the high silicon content (about 19.5 for 14-mil sheet). For solid material the saturation value is about 1 kilogauss higher. Figure 14 gives a magnetization curve for a good grade of this steel. Due to its low saturation value this material cannot be used to advantage in apparatus which must operate at high inductions. The steel is,

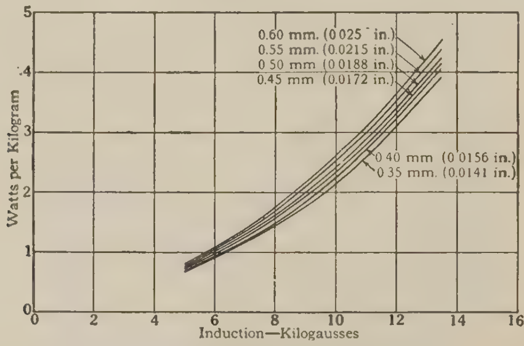

FIG. 18.—Total core loss for medium-silicon steel at 60 cycles per second.

therefore, doubly expensive; first, due to its cost and second, because more steel must be used in order to keep the exciting current low. This material also has certain undesirable mechanical properties. The most common thickness for this class of sheet is about 14 mils (0.036 centimeter). A thinner sheet will decrease the eddy loss, but the space factor will be poorer, thus making it impossible to put as much material in a given space. As the sheet is made thinner, moreover, there is an increase in hysteresis loss, as will be mentioned again in connection with vacuum iron.

The chief use for high-silicon steel is in transformers which are on the line for a large part of the time, such as distributing transformers, where losses are of prime importance. The hysteresis loss for commercial mill-annealed material, 0.014 inch thick, is from 0.015 to 0.025 watt-second per cycle per kilogram, which is lower than for any other commercial electrical sheet. The high silicon is perhaps of as much importance in reducing the eddy losses as the hysteresis. The resulting low combined loss justifies the increased cost. Figure 19 shows the total losses for a good commercial grade of this material. These curves, as well as those in Figs. 16 and 18, show the losses which one manufacturer guarantees will not be exceeded. Obviously, the average loss is less than that shown. As pointed out previously, the eddy-current losses for this high-silicon steel are much higher than the values calculated from the thickness and resistivity.

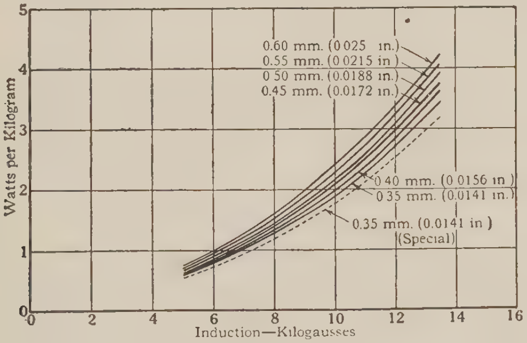

FIG. 19.—Total core loss for high-silicon steel at 60 cycles per second.

Aluminum Steel.—Aluminum has about the same effect on the saturation induction and resistivity in combination with iron as does silicon. For some reason, as yet unknown, it is not nearly as beneficial with reference to the magnetic properties. As reported by Gumlich the saturation induction is given by Fig. 20.

The most complete investigation of iron-aluminum alloys from a magnetic standpoint which has been reported is that of Yensen and Gatward.[1] The magnetic and resistivity results of this investigation from material annealed at 1100°C. are given by Fig. 21. It is seen that an exceptionally good material is found with an aluminum content of about 0.4 per cent, but higher percentages cause a decrease in magnetic quality. Yensen and Gatward summarize their results thus:

1. Aluminum is more powerful as a deoxidizer than is silicon, for it does not commence to combine with iron until all oxides present are reduced. Aluminum forms a solid solution with iron throughout the range studied.

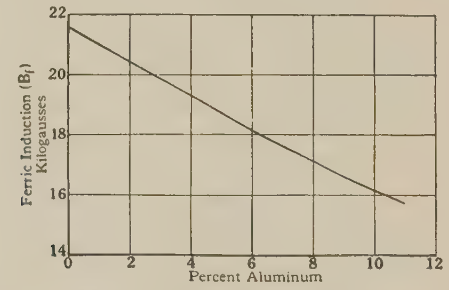

FIG. 20.—Saturation induction of iron-aluminum alloys.

2. The tensile strength of the vacuum alloys increases in direct proportion to the aluminum content up to at least 6 per cent, the ultimate strength of the latter being 85,000 pounds per square inch (60 kilogram per square millimeter) in the unannealed state and 70,000 pounds (50 kilograms) in the annealed. The corresponding figures for pure iron are 48,500 pounds (34 kilograms) and 35,000 pounds (25 kilograms). The toughness is only slightly affected by the aluminum content.

3. With regard to the magnetic properties, aluminum, like silicon, has a very beneficial effect when added in small quantities. The best alloy obtained, containing about 0.40 per cent aluminum annealed at 1100 degrees, has a maximum permeability above 35,000. The hysteresis loss for $B_{\max} = 10{,}000$ and 15,000 is 450 and 1000 ergs per cubic centimeter per cycle, respectively. For higher aluminum contents the magnetic quality decreases gradually, so that the alloy containing 3.5 per cent aluminum has a maximum permeability of 20,000 and a hysteresis loss for the given densities of 1000 and 2200 ergs, respectively. This loss is only one-half that of the 3.5 per cent commercial silicon steel.

4. The specific electrical resistance increases about 12 microhms for each per cent aluminum added. When the aluminum content exceeds 3 per cent, however, the rate of increase falls off gradually.

They arrive at the following conclusions:

By the application of the vacuum process to the iron-aluminum series, an alloy containing about 0.4 per cent aluminum has been produced which has remarkable magnetic properties. In this respect aluminum acts like silicon. Aluminum, however, unlike silicon, yields no alloy with similar characteristics for higher percentages. On the other hand, the high-aluminum alloys have the advantage over the corresponding silicon alloys of being much less brittle; and this characteristic combined with a fairly high permeability, low-hysteresis loss, and an electrical

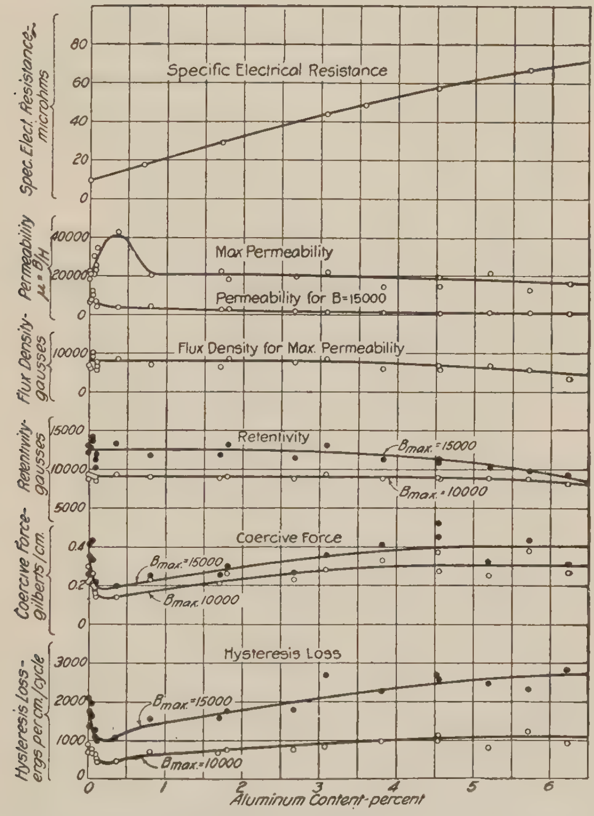

FIG. 21.—Magnetic and electrical properties of iron-aluminum alloys. Melted in vaccum and annealed at 1100°C.

resistance equal to that of the silicon alloys, may make aluminum alloys suitable for certain purposes where the silicon alloys cannot be used.

So far as known, no commercial application has yet been made of iron-aluminum alloys for magnetic purposes. It may be mentioned that it is much more difficult to prevent segregation of aluminum in iron-aluminum alloys than it is to prevent segregation of silicon in the corresponding iron-silicon alloys.

Vacuum Iron.—For some years after the introduction of silicon steel by Hadfield in 1903, there were no radical improvements in electrical steel. There were considerable improvements, to be sure, but they were gradual and chiefly the result of changes in the mill processes, involving only slight changes in chemical composition. In 1914 T. D. Yensen announced very radical improvements in the magnetic properties of pure iron and iron-silicon alloys when prepared in a vacuum furnace and annealed in a vacuum, or under nonoxidizing conditions, at fairly high temperatures.[2] Maximum permeabilities of about 40,000 were obtained on ring samples, and hysteresis losses of about one-fourth those hitherto observed for the best silicon steel. These remarkable magnetic properties were the result of reducing the impurities, particularly carbon, to a minimum. Later researches showed quantitatively the effect on the magnetic properties of these various impurities and alloying elements common to electrical

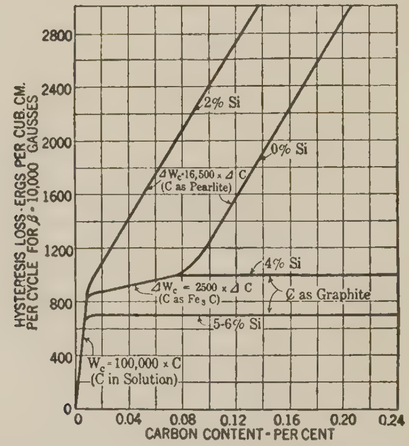

FIG. 22.—Effect of carbon on the hysteresis loss of iron-silicon alloys. All other impurities and effect of grain size eliminated.

steel. These results are of such fundamental importance in connection with the magnetic properties of materials that they will be considered in some detail. They are summarized in a recent article by Yensen.[3]

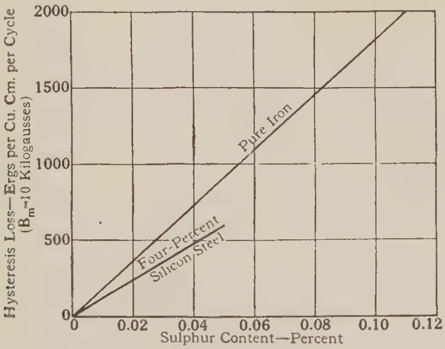

Fig. 23.—Effect of sulphur on the hysteresis loss of pure iron and 4 per cent silicon steel.

Several grades of material were experimented with, including pure iron with an electrolytic-iron base, and silicon steel with various percentages of silicon. Figure 22 shows the effect of carbon on hysteresis loss, Fig. 23, the effect of sulphur, Fig. 24 the effect of manganese, and Fig. 25 the effect of phosphorus. Low hysteresis, of course, is accompanied by low coercive force, high maximum permeability, etc. Three of these relationships

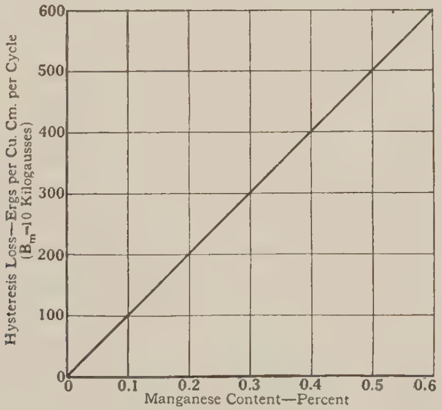

Fig. 24.—Effect of manganese on the hysteresis loss of pure iron and 4 per cent silicon steel.

are given in Figs. 26, 27, and 28. The high-induction permeability and the saturation are little affected by the variations commonly met with in these elements.

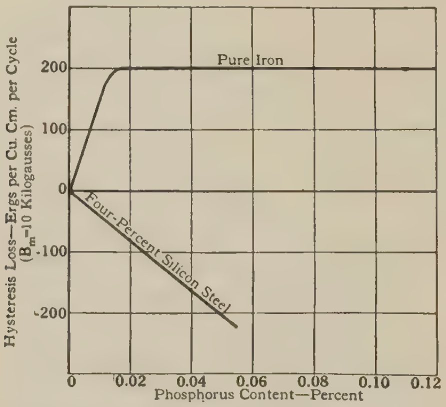

FIG. 25.—Effect of phosphorus on the hysteresis loss of pure iron and 4 per cent silicon steel.

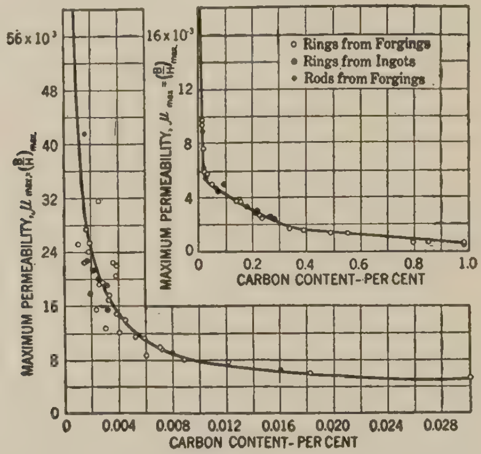

FIG. 26.—Effect of carbon on the maximum permeability of iron. Containing no silicon. No correction made for incidental impurities or grain size.

The large effect of very small amounts of carbon on the magnetic properties is striking. The ordinary methods of chemical analysis were quite inadequate to determine accurately carbon percentages of less than a few hundredths of 1 per cent, although these small quantities of carbon very considerably affect the magnetic properties. New methods, therefore, had to be developed to enable reliable studies of the relation between carbon content and magnetic properties to be made.[4] From Fig. 22, it is seen that for carbon in solution up to about 0.008 per cent the hysteresis loss is approximately proportional to the carbon, apparently aproaching zero for no carbon. The rate of increase of loss is very high. For the higher percentages, the action of carbon is different, depending on the silicon percentage. For low and medium-silicon steel, the loss increases with carbon content but at a much slower rate. For high-silicon steel the effect of additional carbon is practically zero. This is evidently due to the fact that the silicon throws the carbon out of solution in the form of neutral graphite. It should be understood that before plotting these curves the effect of the other impurities was calculated and the losses reduced by a corresponding amount.

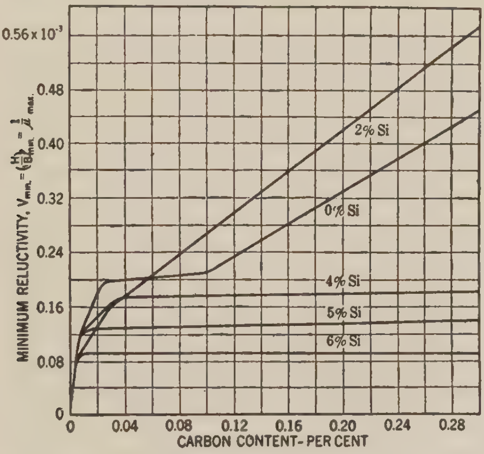

FIG. 27.—Effect of carbon on the minimum reluctivity (reciprocal of maximum permeability) of iron-silicon alloys.
No correction made for incidental impurities or grain size.

The next element in importance, as far as it affects the magnetic properties, is sulphur. Even in quite small percentages this element is very harmful. Manganese and phosphorous have only a small effect.

There is another factor besides chemical composition which is of considerable importance, namely, grain size. The larger the grains the better the magnetic properties, other things being equal. Silicon aids very greatly in grain growth,[5] which is one reason why silicon steel has such good magnetic properties. It is not uncommon in commercial high-silicon sheet to find grains 0.25 inch or more across. The individual crystals in this class of material are usually visible without the use of a microscope.

Yensen has developed formulas from which the hysteresis loss of a sample of pure iron or silicon steel may be predicted quite accurately if the chemical composition and average grain size are known. These formulas are given in equations (35) to (40). For all silicon contents considered in these formulas, the carbon is in solution up to percentages of from 0.006 to 0.008. For higher carbon percentages the carbon may be in a number of forms, such as iron carbide, pearlite, or graphite, depending on the amount of carbon and silicon. The form in which the carbon appears determines its effect on the magnetic properties. It will be seen that these formulas correspond to the curves of Figs. 22 to 25. It should be understood, of course, that they will hold only for material which has been suitably annealed under conditions which will not permit overoxidation.

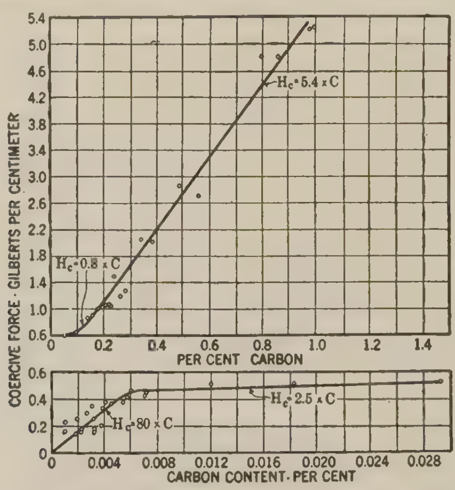

FIG. 28.—Effect of carbon on the coercive force of iron. Containing no silicon. No correction made for grain size.

Carbon in Solution (low carbon),

Zero to 2 per cent silicon—

$$W_h = 65\sqrt{N} + 100{,}000\text{C} + 18{,}000\text{S} + 1{,}000\text{Mn} + 13{,}000\text{P}. \tag{35}$$

Upper limits: C = 0.006 S = 0.01 Mn = 0.06
P = 0.015 per cent.

Four to 6 per cent silicon—

$$W_h = 65\sqrt{N} + 100{,}000\mathrm{C} + 12{,}000\mathrm{S} + 800\mathrm{Mn} - 4{,}000\mathrm{P}. \tag{36}$$

Upper limits: C = 0.008 S = 0.05 Mn = 0.16
P = 0.05 per cent.

Precipitated carbon (Fe_3C, pearlite, graphite),

Zero silicon—

$$W_h = 3N + 800 + 2{,}250(\mathrm{C} - 0.008) + 16{,}500(\mathrm{C} - 0.09) + 18{,}000\mathrm{S} + 1{,}000\mathrm{Mn} + 13{,}000\mathrm{P}. \tag{37}$$

Upper limits: C = 0.09 C = 0.90
S = 0.10 Mn = 0.60 P = 0.015 per cent.

Two per cent Silicon—

$$W_h = 3N + 800 + 16{,}500(\mathrm{C} - 0.008) + 18{,}000\mathrm{S} + 1{,}000\mathrm{Mn} + 13{,}000\mathrm{P}. \tag{38}$$

Upper limits: C = 0.50 S = 0.10
Mn = 0.60 P = 0.015 per cent.

Four per cent silicon—

$$W_h = 3N + 800 + 2{,}250(\mathrm{C} - 0.008) + 0(\mathrm{C} - 0.08) + 12{,}000\mathrm{S} + 800\mathrm{Mn} - 4{,}000\mathrm{P}. \tag{39}$$

Upper limits: C = 0.08 C = 10
S = 0.05 Mn = 0.16 P = 0.05 per cent.

Six per cent silicon—

$$W_h = 3N + 700 + 0(\mathrm{C} - 0.007) + 12{,}000\mathrm{S} + 800\mathrm{Mn} - 4{,}000\ \mathrm{P}. \tag{40}$$

Upper limits: C = 1.0 S = 0.05 Mn = 0.16
P = 0.05 per cent.

Where W_h = hysteresis loss in ergs per cubic centimeter per cycle, N = number of grains per square millimeter and the other symbols represent the percentages of the chemical elements designated.

In order to obtain very low hysteresis loss, it is necessary to take the greatest pains in selecting the raw materials and in carrying out the furnace practice, rolling, and heat-treatment. Carbon contamination, especially, must be avoided. Instead of starting in with carbon-free material, Yensen has shown that it is possible to take commercial electrical steel preferably in the sheet-bar form and by suitable oxidizing treatments remove most of the carbon with the result that very considerably improved magnetic properties are obtained. Due to the fact, however, that sulphur cannot be removed by this process, the resulting magnetic properties are not as good as when sulphur-free iron such as electrolytic iron is used as a base.

Gumlich* also clearly points out the necessary for keeping the carbon content as low as possible. His results evidently have had a strong influence on the German furnace practice in the manufacture of electrical sheet. According to recent reports, a large part of the high-grade sheet is made in induction furnaces because this type of furnace lends itself especially well to the reduction of impurities, particularly carbon.

There is one factor which limits the benefit to be obtained from the low hysteresis loss of this vacuum iron, namely the eddy-current loss. As was previously mentioned, the eddy loss increases with the grain size. Also, as has just been shown, large grains are apparently necessary for low hysteresis loss. In order to obtain low total core loss it is, then, necessary either to increase the resistivity or to decrease the thickness of sheet. It is difficult to increase the resistivity; therefore, it may be that the most economical thickness for vacuum steel will be somewhat less than is now the practice for electrical sheet.

Aside from the advantage to be gained from the low hysteresis loss of vacuum steel, there are certain applications which can make use of the very low coercive-force characteristics. For instance, the first commercial use of this material was for the yokes of automobile ammeters.[6] If a material of this nature, giving very low residual for the yokes, had not been available, the meter would have been a failure, since there would have been a considerable zero shift after a reversal of current. This steel also makes excellent meter vanes.

Nickel.—This element by itself is of little importance as a magnetic material. As an alloying element, however, it is of very great importance. It has an initial permeability of about 250. The maximum permeability is about 400 at an induction of from 400 to 3000 depending on the silicon and manganese contents. Its saturation value is about 6.5 kilogausses, which is less than one-third that of iron. For a maximum induction of 4 kilogausses, its hysteresis loss is about 0.06 watt-seconds per cycle per kilogram, and its coercive force is about 5. Its resistivity is approximately 7 microhm-centimeters.

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* Gumlich at the Physik-Techn. Reichsanstalt in Germany has investigated the relation between the chemical composition and magnetic properties of iron and steel in much the same way as Yensen; but his work was apparently not as exhaustive in that he did not obtain such definite quantitative results as did Yensen. He has perhaps, however, covered a somewhat wider field. A good account of his work is given in the *Elektrotech. Z.* for June and July, 1919. The parallel work of Yensen and Gumlich should be of great benefit to the electrical sheet producers and users.

It is now evident why nickel by itself is of such little value magnetically. Its saturation value is low and its hysteresis loss is high with low permeability at all inductions.

Cobalt.—In common with nickel, cobalt by itself has little importance as a magnetic material, but it is a very useful alloying element. It has one property among magnetic materials, however, which is unique; namely, it retains its ferromagnetic characteristics at higher temperatures than any other known material. Its magnetic transformation point is about 1150°C. Cobalt has a maximum permeability of about 150 at an induction of 3 kilogausses. Its saturation value is said to be about 17 kilogausses, but this value is in doubt, due to the difficulty of obtaining pure material. Its resistivity is about 97 microhm-centimeters.

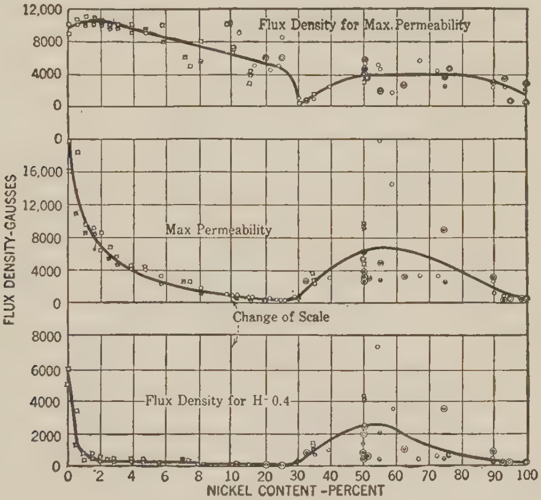

FIG. 29.—Relation between nickel content, flux density, and permeability for iron-nickel alloys.

Iron-nickel Alloys.—This series has been investigated for magnetic properties by a number of experimenters.[7] Perhaps the most complete investigation has been reported by Yensen.[8] His results are summarized by Figs. 29, 30, 31, and 32. The electrical resistivity is given by Fig. 33 and the density by Fig. 34.

Yensen's results are particularly valuable, since his alloys were made from the purest obtainable materials and the melting and heat-treating operations were carried on under nonoxidizing conditions.

It is evident that by the proper choice of nickel content almost any magnetic characteristic desired may be obtained. The critical point at a nickel content of about 30 per cent is particularly interesting. It will be noted that at this point the material becomes nearly nonmagnetic with a sharp increase in hysteresis loss. This discontinuity is the result of a sudden change in the atomic structure of the material.[9] The iron atom, as shown by *X*-ray analysis, has a cubic body-centered structure, while nickel has a cubic face-centered structure. When the nickel content of the nickel-iron series passes 30 per cent, the atomic arrangement changes from the iron structure to the nickel with profound changes in the magnetic properties. In the transition range, the structure may be chiefly of one kind or the other, with both present simultaneously.[10]

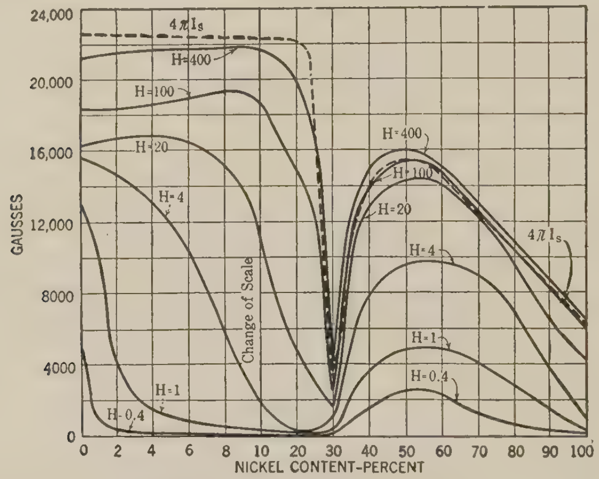

FIG. 30.—Relation between nickel content and flux density at various magnetizing forces for iron-nickel alloys.

For small percentages of nickel, the high-induction permeability is slightly increased, although the saturation value decreases with increasing nickel content. With slow cooling during the annealing cycle, as used by Yensen, the hysteresis loss and coercive force are a minimum at about 50 per cent nickel, approxi-

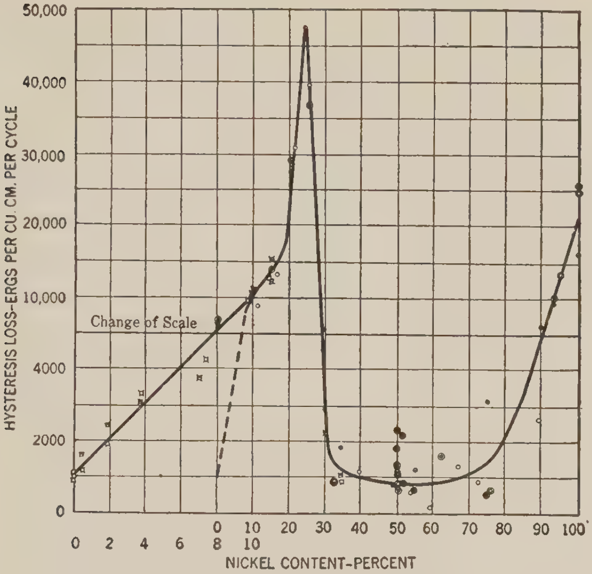

FIG. 31.—Relation between nickel content and hysteresis loss (B_m = 10 kilogausses) for iron-nickel alloys.

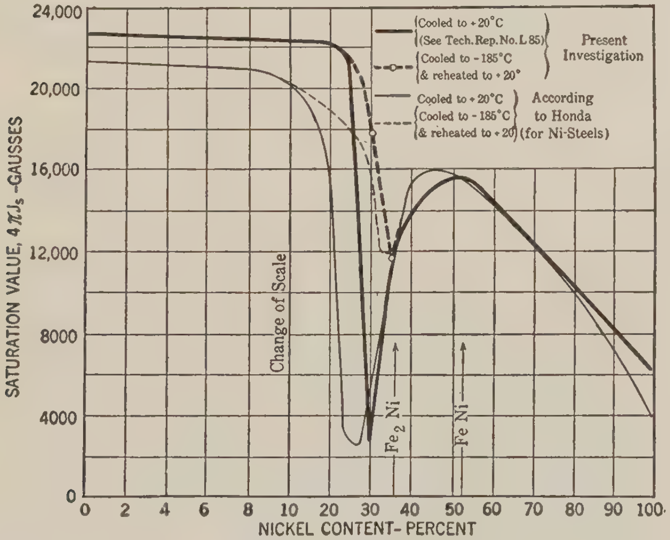

FIG. 32.—Relation between nickel content and saturation induction for iron-nickel alloys.

mately equaling the values for pure iron. The retentivity in this range is usually quite low as compared with iron. When it is desired to use these alloys under a.-c. conditions, the resistivity becomes of importance. As seen from Fig. 33 the 50 per cent alloy has a fairly high resistivity.

Recently, there has been discovered a very remarkable nickel-iron alloy called by the discoverers *permalloy*.[11] This alloy was developed by the Western Electric and American Telephone and Telegraph companies, primarily for use in loading coils and similar applications where high permeability at low inductions is required. By its use in the form of a thin ribbon wrapped spirally around, and adjacent to, the central conductor of a long submarine cable which had recently been installed, the speed of working of the cable has been increased fivefold. This material is a very pure iron-nickel alloy having a nickel content of about 78.5 per cent. Under favorable conditions it may have an initial permeability of about 9000 and a maximum permeability of over 100,000 at an induction of about 5 kilogausses. Its saturation value is about 11 kilogausses. Its hystersis loss is one-tenth or less that of ingot iron. Figures 35 to 38 show the exceptional properties of this alloy as compared with Armco iron.[11]

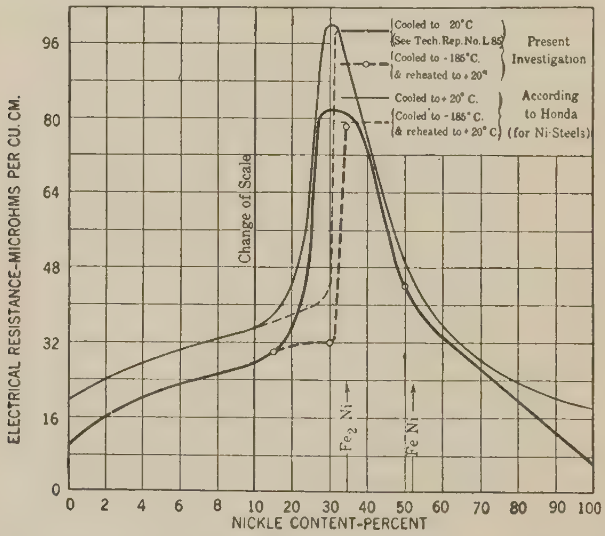

FIG. 33.—Relation between nickel content and electrical resistance for iron-nickel alloys.

These exceptional permeability and hysteresis values are obtained by an annealing treatment which is quite different from that which gives the most favorable results for other known magnetic materials, which is probably the reason why this alloy remained so long undiscovered. It is generally the case that very slow cooling yields the highest permeability and the lowest hysteresis loss. For permalloy, however, the rate of cooling from the magnetic critical point (625°C.) down to 300°C. must be as rapid as possible, provided only that it is not so rapid that it introduces mechanical strains into the material. This alloy may readily be rolled into thin sheets or ribbon, and is therefore suitable for use under a.-c. conditions, especially at higher frequencies, such as are met with in the telephone art. Its resistivity is much lower than for many alloys (20 microhm-centimeters)

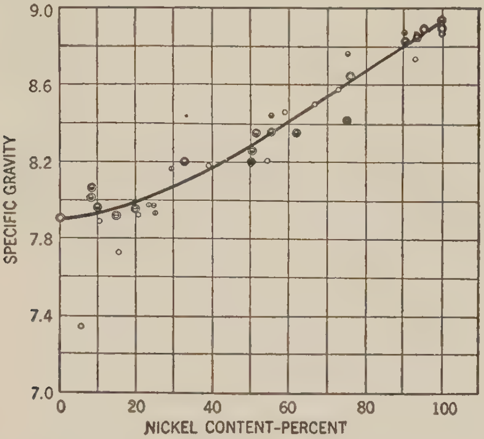

Fig. 34.—Relation between nickel content and density for nickel-iron alloys.

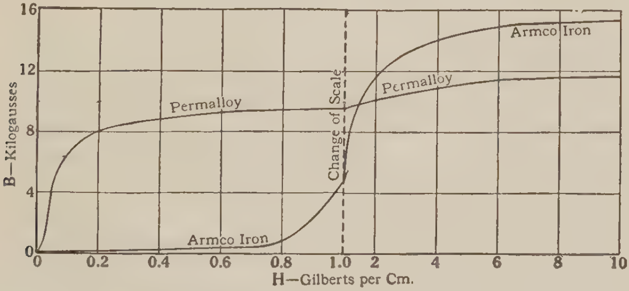

Fig. 35.—Comparison of normal induction of Armco iron and permalloy.

but this is not a serious matter since quite thin sheets can easily be obtained. There is, however, one important limitation to the material; namely, it is very susceptible magnetically to mechanical strains. Stresses below the elastic limit may reduce the initial or maximum permeability to a very small percentage of the unstressed values. For the best results, it is necessary to shape the material to its final form and then anneal it in that condition. As might be expected from the above, this alloy shows large dimensional changes, relatively, when magnetized.

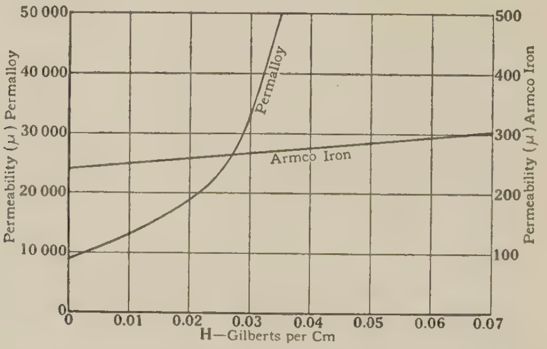

FIG. 36.—Permeability of permalloy compared to that of Armco iron for low magnetizing forces.

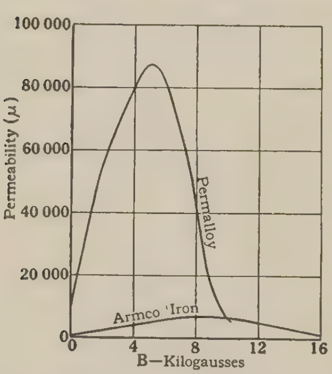

FIG. 37.—Comparison of permeability of permalloy and Armco iron with respect to induction.

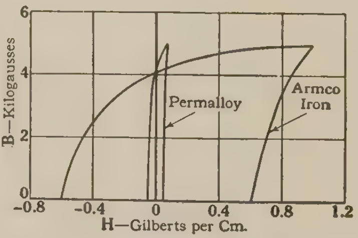

FIG. 38.—Comparison of hysteresis loops for Armco iron and permalloy.

Referring to the magnetization curve for permalloy, Fig. 35, it will be seen that the material approaches saturation at a field strength of about 0.2 gilbert per centimeter. This means that the alloy will nearly saturate in the earth's field. In this connection it may be pointed out that, if a strip of permalloy is placed in a north-south position, it will have approximately 0.3 per cent less resistance than if placed in an east-west position. It is possible to produce a change of 2 per cent in resistance by applying a field of 1 gilbert per centimeter.

For the best results, this alloy must be made of pure materials, carbon being especially harmful as is the case for Yensen's iron-silicon alloys. It perhaps can be best prepared in a high-frequency induction furnace, using an electrolytic-iron base.

As given by Arnold and Elmen,[11] the relation between initial permeability and nickel content after being subjected to suitable heat-treatment is shown by Fig. 39. For the 50 per cent nickel-steel the initial and maximum permeabilities are about the same for either slow or moderately rapid cooling. The hysteresis loss is much less than that for the best commercial silicon steel, and the electrical resistance is about double that of permalloy.

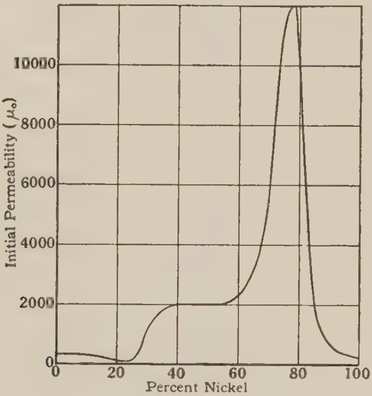

Fig. 39.—Initial permeability of pure iron-nickel alloys.

An alloy of 50 per cent nickel-iron has certain very desirable properties which make it useful for certain applications. It has been used, for instance, quite extensively for the cores of audio-frequency transformers. Initial permeabilities of 3000 can be obtained by using sufficiently pure materials properly heat-treated, with corresponding maximum permeabilities of 50,000 or more. This alloy has the advantages over permalloy that it can be heat-treated by the ordinary process of slow cooling from the maximum temperature, and the good properties can be obtained without going to very thin sheets. The best results are obtained by annealing from a fairly high temperature, 1000 to 1200°C. in a hydrogen atmosphere. Pure alloys made from electrolytic iron and melted in an induction furnace are superior to those made by the ordinary metallurgical means; but even the latter process is capable of giving useful alloys of good magnetic quality.

At present the applications of these nickel-iron alloys are quite limited and probably always will be, due to the low saturation values. When the apparatus is to work at low inductions, as is the case for telephone loading coils, for instance, some of these alloys may be very useful, but for ordinary transformers they probably will be out of the question, even though a sufficiently cheap supply of nickel were available. From the standpoint of magnetic theory and for a study of magnetic properties as affected by various influences, these alloys are of the utmost importance.

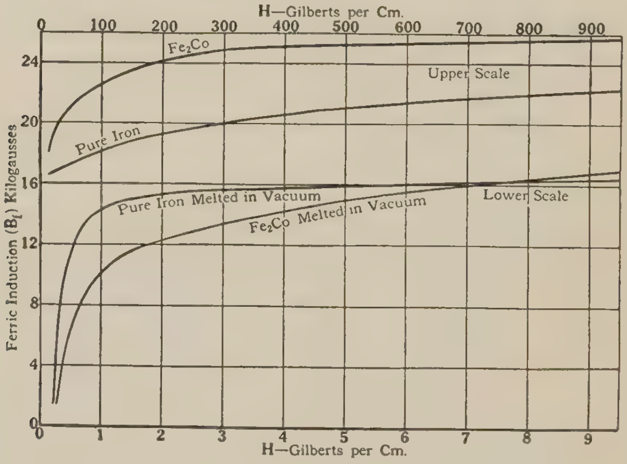

FIG. 40.—Comparison of Fe_2Co and pure iron with respect to induction.

Iron-cobalt Alloys.—There is at present, at least, only one range in the pure iron-cobalt series which is of particular interest; namely, near the composition corresponding to Fe_2Co or 34.5 per cent cobalt. It has been shown by Weiss[12] that the addition of cobalt to iron in this percentage increases the saturation value about 12 per cent. This is the only known material having a saturation value much higher than that of iron. Figure 40 gives a magnetization curve for this alloy as compared with pure iron.[13] At values of H from 50 to 200 gilberts per centimeter the inductions are about 25 per cent higher than for iron. According to Yensen, for very pure vacuum-fused material the maximum permeability is about 13,200 at 8 kilogausses induction. For a maximum induction of 10 kilogausses, the coercive force is about 0.48 and the hysteresis loss 0.17 watt-second per cycle per kilogram. The resistivity is slightly less than 10 microhm-centimeters or about the same as that of pure iron.

If it were not for the expense, this alloy would be very widely used. Unfortunately, however, there is little hope that cobalt ever will be sufficiently cheap that this alloy can be used to any considerable extent commercially. It is frequently used to advantage for the pole pieces of electromagnets where the advantage far outweighs the expense. In the form of permanent-magnet steels with other alloying elements, cobalt may be of considerable commercial importance.

Iron-manganese Alloys.—These alloys are of special interest because of the fact that with sufficient manganese present they become non-magnetic. Figure 41 gives the saturation induction as obtained from data supplied by Gumlich[14] for manganese steel when quenched from 800°C.

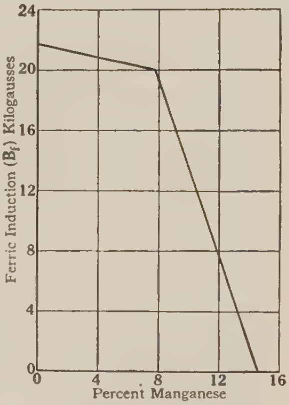

FIG. 41.—Saturation of iron-manganese alloys.

Heusler Alloys.—From a theoretical standpoint, probably the most interesting ferromagnetic materials are the Heusler alloys, because their constituents are nonmagnetic. These alloys, which derive their name from their discoverer,[15] may consist of a combination of a number of different elements, but the most highly magnetic contain copper, manganese, and aluminum. Most of the following information has been obtained from two sources,[16,17] part of it being taken verbatim from Knowlton's paper. The chief characteristics of Heusler alloys are as follows:

1. The magnetic permeability of the best specimens after proper heat-treatment is about that of poor cast iron, and the hysteresis loss is about that of poor cast steel. Good samples will saturate at from 6 to 7 kilogausses.

2. The best heat-treatment seems to be to quench the material and then anneal it for a long time at a temperature slightly over 100°C. The magnetic transformation covers a range of temperature of 50° or more. For the best alloys the nonmagnetic state is reached in the neighborhood of 300°C. Annealing at the temperature corresponding to the beginning of the transformation range leaves the material very hard and with low maximum induction, while annealing at the upper limit followed by rapid cooling softens the specimen and increases the maximum induction.

3. The most strongly magnetic alloys were found by Heusler and Stark to be those containing manganese and aluminum in atomic proportions, in the ratio of two parts, by weight, of Mn to one of Al. Largely upon these grounds, it has been quite generally assumed that copper plays no part in the alloy except as a solvent for a manganese-aluminum alloy which otherwise would be too hard and brittle for experimental use. Knowlton has shown, however, that the copper has an important influence on the magnetic properties, especially the transformation temperatures. A high ratio of copper to manganese lowers the transformation temperature. The following composition has a magnetic transformation point near zero centigrade; copper 72.2 per cent, manganese 17.4 per cent, aluminum 10.3 per cent.

4. Typical compositions for good alloys are as follows:

Element	Per Cent	
	B. of S.	Knowlton
Cu	64.5	59.7
Mn	20.4	28.3
Al	13.2	11.7
Si	0.08	0.24
Fe	1.05	
Pb	0.07	

Other trivalent elements, such as arsenic, antimony, or tin, may be substituted for the aluminum, but the alloys thus obtained are much inferior magnetically.

5. The Hall effect is very large and of the same sign as for iron, but there is apparently no Kerr effect, which is the only way in which these alloys differ markedly from iron.

6. The resistivity for good magnetic alloys ranges from 45 to 65 microhm-centimeters. The resistivity may be very considerably decreased by continued heating at temperatures from 120°C. up to the nonmagnetic point. Quenching increases the resistivity.

7. Knowlton has shown that the magnetic properties are apparently a function of the amount of white crystals present in the alloy, these crystals being shown by the use of an etching solution of HCl and $FeCl_3$.

So far as known these alloys have no commercial application but, due to their theoretical interest, they cannot be ignored. It seems probable that the ferromagnetic properties are due to the existence of the manganese in a form different from its normal state. While manganese is normally nonmagnetic, yet it has properties in common with iron, nickel, and cobalt. It has been suggested, therefore, that the presence of aluminum or a similar element may cause the manganese to assume a ferromagnetic condition. In line with recent theories of atomic structure, perhaps a better suggestion would be that the ferromagnetic properties of these alloys are due primarily to the presence of the manganese and copper with the aluminum merely acting as an aid in producing the magnetic state. Manganese has an atomic number just below that of iron, nickel, and cobalt, while copper is just above. It seems probable that in some way the deficiency of the manganese in electrons or charges on the positive nucleus (if one of these is the cause of ferromagnetism) is made up by the surplus of the copper, thus giving a structure similar to that of the highly magnetic elements. When more is known of the structure of the atom and the nature of magnetism, it is probable that the explanation of the properties of these Heusler alloys will be very simple.

Non-magnetic Steels.—Although ferromagnetic materials are being discussed here, it seems proper to include a short description of certain nonmagnetic ferrous alloys. In the section on nickel-iron alloys it was shown that, with a composition of about 30 per cent nickel, it was possible, with proper thermal treatment, to obtain a practically nonmagnetic material. This is true, however, only if the alloys contain a small amount of other alloying elements such as manganese or carbon. Yensen[8] has shown that for pure iron-nickel alloys the retentivity is quite high, even for the 30 per cent nickel content. These other alloying elements serve to depress the temperature of the magnetic transformation to a point below room temperature. Chromium is especially suitable for lowering this transformation point. A commercial nonmagnetic steel of this type having a permeability at moderate magnetizing forces of less than 10 has the following composition:

C	0.3	per cent
Mn	0.68	per cent
P	0.01	per cent

S	0.031 per cent
Si	1.57 per cent
Ni	22.73 per cent
Cr	7.25 per cent
Fe	remainder

A somewhat similar alloy having 17 per cent nickel, 4.5 per cent chromium and 3.0 per cent manganese is said to have a permeability of 1.004.

Hadfield's nonmagnetic steels have about 12 per cent of manganese as their chief constituent besides iron. The principal alloying elements of one practically nonmagnetic alloy as reported by Hadfield are as follows:

C	1.25 per cent
Si	0.43 per cent
Mn	12.20 per cent

Annealing at 500°C. makes this alloy quite magnetic. These steels are useful where the nonferrous alloys are not strong enough mechanically, but where the nonmagnetic properties are essential.

Nonmagnetic Cast Iron.—There has recently appeared on the market a nonmagnetic cast iron which, due to its less cost and greater machinability, should have some advantages over the steels for certain applications. It is said to have a permeability of about 1.06 over a wide range of magnetizing force. The composition is approximately as follows:

C (combined)	0.16 per cent
C (graphite)	2.49 per cent
Si	2.54 per cent
Mn	5.88 per cent
S	0.034 per cent
P	1.10 per cent
Ni	9.42 per cent

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CHAPTER V

PERMANENT-MAGNET STEELS

The chief essentials of a good permanent-magnet steel are high coercive force, high residual induction, and magnetic permanency. The relative importance of these three characteristics depends on the application. In some cases first cost is more important than the magnetic properties. Under these circumstances plain carbon steel or even cast iron may serve. In most cases, however, a relatively expensive alloy steel is required. Up to the time of the World War, tungsten magnet steels were used almost exclusively for meters and magnetos. Due to the scarcity of tungsten at that time, extensive experiments were made with chromium steels as a substitute, and it was found that the latter were practically as satisfactory and appreciably cheaper. Recently, Honda[1] has published information on some new alloys which have properties superior to the ordinary tungsten and chromium steels. These various types of magnet steels will be discussed individually.

Perhaps the most extensive published researches on permanent-magnet steels are those of Madame Curie, but there have been many advances in the art since her work was published. One of the most complete and valuable papers on the subject was presented by S. P. Thompson in 1913[2]. Besides being a very satisfactory resumé of the state of the art up to that time, it also contains a very good bibliography. Kelley in 1917[3] gave a much shorter but fairly complete review of the subject. Gumlich in Germany has published a number of very valuable articles on the subject. Burgess and Aston[4] have done some very good research work on the subject showing the effect of varying alloying elements on the magnetic properties. A most excellent article by Evershed,[7] dealing with the theory and design of permanent magnets, appeared in 1920 and was followed in 1925 by another exceptionally able article dealing chiefly with the composition and heat-treatment of magnet steel, with special reference to tungsten steels. Finally, also, in 1925 Mathews[6] published a most instructive article dealing with retained austenite and its relation to permanent-magnet steels. Except as otherwise noted, most of the information contained in this chapter has been obtained from the above sources.

Due to the fact that the manufacturers and users of permanent-magnet steel seldom publish anything concerning their researches on the properties of these alloys, it is probable that much of the best work is not available. Doctor Mathews' articles published in 1914 and 1925 are notable exceptions.[5,6] Some manufacturers, moreover, follow rule-of-thumb and conventional practices as regards composition and heat-treatment, which doubtless could be appreciably improved if there were a wider dissemination of knowledge on the subject. It is quite possible that some of the manufacturers may have positive information which is quite at variance with what may be said here.

GENERAL PROPERTIES OF PERMANENT MAGNETS

Before discussing specific magnetic materials, it will be well first to consider in some detail the necessary characteristics in connection with the completed magnetic circuit. In order that a permanent magnet shall deliver useful flux, there must exist somewhere in the magnetic circuit an appreciable air-gap. For certain electrical measuring instruments the air-gap may be quite small; for the compass needle, it is very large. A part of the m.m.f. of the magnet must be used up in overcoming the reluctance of the air-gap. The flux density in the magnet, especially near the gap, is lessened. It may be considered that magnetic poles, which are produced by virtue of the air-gap, exert a demagnetizing effect. This demagnetizing effect, as shown by Ewing and as described later by Thompson, acts in the following manner:

Referring to Fig. 42, the heavy lines show a hysteresis loop for a given material with the normal values of B_m, B_r, and H_c as indicated. Now, with a closed magnetic circuit, if H is decreased from H_m to H_1, the corresponding induction will be B_1. If, however, there is an air-gap, the effective H will be less due to the demagnetizing effect. If it is assumed that this demagnetizing effect is the same for all inductions and that there is no magnetic leakage this effect may be represented by the line B_2H_1 making an angle α with B_1H_1. The tangent of α is numerically equal to the demagnetizing coefficient (to be considered later), if B and H

are to the same scale. If there is not the case, the plotted angle must be such that the tangent is equal to the numerical value of the demagnetizing coefficient multiplied by the ratio of the scales used for B and H. Referring again to Fig. 42, the effect of the air-gap is to reduce H_1 to H_2, which gives the corresponding value for induction of B_2. Now, if the applied magnetizing force is removed entirely, the residual induction will be B_r for the closed magnetic circuit, but with the air-gap will be B_3 as indicated. H_3 is the demagnetizing force due to the poles produced by the air-gap. Evershed has recently devised a more exact method of analysis, taking into account the effect of magnetic leakage, which will be considered a little later. B_3 may be called the apparent residual induction as distinguished from the true value B_r.

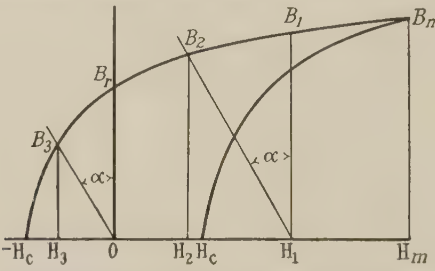

FIG. 42.—Hysteresis loop showing demagnetizing effect of air-gap.

Demagnetizing Coefficient.—The demagnetizing coefficient is shown by the following relation as given by Ewing:

$$H = H_1 - DJ \qquad (41)$$

where H = resultant magnetizing force;
H_1 = magnetizing force which would exist if there were no iron present;
D = demagnetizing coefficient;
J = intensity of magnetization.

If desired, this equation may be written in the following form:

$$H = H_1 - D_B B_f{}^*, \qquad (42)$$

where $D_B = \dfrac{D}{4\pi}$;
B_f = ferric induction = $B - H$.

---

* When the applied field is reduced to zero, B_f corresponds to $B_3 - H_3$ of Fig. 42. In this case $H = -D_B B_f$.

For a long rod or ellipsoid, these demagnetizing coefficients may be readily calculated. For most magnetic circuits, however, they may be merely approximated. For an ellipsoid, the formula is as follows:

$$D = 4\pi\left(\frac{1.1513}{e}\log_{10}\frac{1+e}{1-e} - 1\right)\left(\frac{1}{e^2} - 1\right). \qquad (43)$$

Where $e = \sqrt{1 - \frac{a^2}{c^2}}$,

a = the minor axis of the ellipsoid, and
c = the major axis.

Figure 43 shows the demagnetizing coefficients (D_B) as given by Thompson. They are slightly different from those given by the above formula as they are for rods instead of ellipsoids. It will be noted that these coefficients depend only on the ratio of the length to the diameter of the specimen.

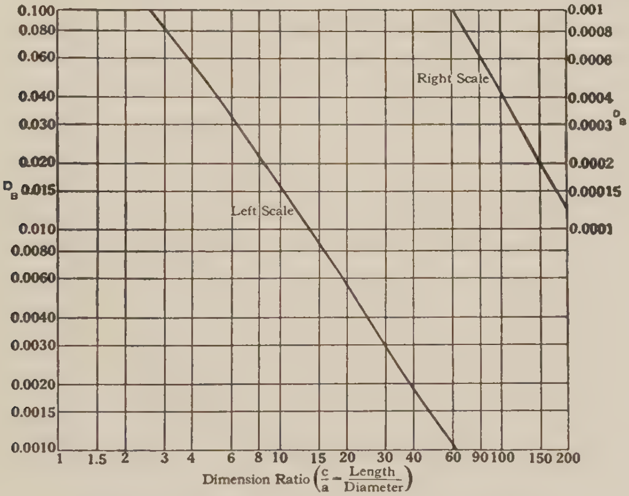

Fig. 43.—Thompson's demagnetizing coefficients.

For the usual type of permanent magnet with a comparatively small air-gap, a different kind of formula has to be used. A common form is the following:

$$D = \frac{4\pi}{\gamma}\left(\frac{l_g}{l_m}\frac{A_m}{A_g}\right), \qquad (44)$$

where l_g = width across gap in centimeters;
l_m = mean length of path along core;
A_m = cross-section of core in square centimeters;
A_g = cross-section of gap;
γ = leakage coefficient.

The leakage coefficient is the ratio of the total flux in the magnetic core at the middle to the useful flux in the gap. By using pole pieces of large cross-section or a very narrow gap, γ may be kept reasonably near unity. It is stated that for a satisfactory magnetic circuit the value in the brackets must not exceed one-seventieth. This does not hold, however, for some of the recent cobalt steels. The above formula gives D_B if 4π is omitted.

Magnet-steel Criteria.—Evershed has shown that it is possible to predict quite accurately the performance of a permanent magnet in a given magnetic circuit, or to design such a circuit properly by dividing the circuit into a number of sections and calculating the flux conditions for each section separately.[7] It is beyond the province of this book to consider the design of complete apparatus, but the fundamental characteristics of materials may be examined with profit. For details of design not covered here, Evershed's excellent paper[7] should be consulted. He shows that one of the most important characteristics of a magnetic material for use as a permanent magnet is the maximum available magnetic energy. Referring to Fig. 9,* this energy is obtained as the product of B and H for the demagnetizing curve of the material. The maximum value of this product is an essential factor in Evershed's calculations and will be called $(B_dH_d)_{\text{max}}$.

Crapper[8] has recently caused considerable discussion on the subject of magnet-steel specifications.† It was formerly thought that the coercive force was the one important characteristic from which to determine the strength and constancy of a magnet steel, the value of the retentivity being considered of secondary importance. For some time it has been thought in Germany that the product $B_r \times H_c$ is the chief characteristic from which to judge the value of a magnet steel. In England recently, much prominence has been given to the above-mentioned factor $(B_dH_d)_{\text{max}}$. It is desirable also to know the value of B at which this occurs.

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* See Chap. III.

† This discussion appears in various numbers of *Engineering* for the first half of 1923.

As a measure of stability, Crapper proposes the coefficient of retentivity $c = \frac{B_r}{B_{\max}}$, which should not be less than some assigned value, such as 0.625 for instance. He also suggests that the product $H_c \times c$ might be useful. Finally, he thinks that the specific reluctivity at the remanence point $\frac{H_c}{J_r}$ might be an indication of permanency. Doctor Mathews considers that the "specific retentivity" $\frac{B_r}{H_c}$ is a very useful factor in connection with permanent-magnet stability. According to him, for a given type of steel, the smaller this factor the better, assuming of course that B_r is not so small as greatly to reduce the available flux.

Before the full value of any of these factors can be determined, much more research is necessary, the factors which correlate with permanency being especially open to doubt. It is known, however, that when there is a large demagnetizing coefficient, H_c must be large, and that when the demagnetizing coefficient is small, B_r should be large. It is also known that, if the expense is not prohibitive, $H_c \times B_r$ or $(B_d H_d)_{\max}$ should be as large as possible. If one of these last factors is large, the other will be large also, but with different heat-treatments, for instance, they may change by somewhat different ratios. Specific values for some of these factors for different classes of material will be given later.

Another factor of importance in connection with permanent magnets is the incremental permeability.* This has to be known when studying the effects of large changes in the reluctance of the magnetic circuit such as occur when removing or inserting pole pieces or when considering the effect of alternating m.m.fs.

In a recent article on permanent magnets[9] considerable use is made of the so-called open-circuit coercive force, by which is meant the reverse magnetizing force necessary to leave the sample in a state of zero magnetization after the magnetizing force has been removed. Its value is not a constant of the material, but is a function of the dimension ratio of the sample, unless the test is made by means of a permeameter or the sample has a closed magnetic circuit. A moment's consideration will show the real nature of the open-circuit coercive force. The true H_c value is that obtained under closed- or open-circuit conditions when the demagnetizing force is just sufficient to reduce the residual induction to zero while the demagnetizing force is still applied. If the H_c value of magnetizing force is removed, the induction will rise to a point *a* as indicated by Fig. 44. The open-circuit coercive force (ocH_c) is the demagnetizing force of such value that, if it is removed, the induction will rise to zero; thus, a demagnetizing force ocH_c will cause the induction to drop to a point *b* before it is removed. If this is determined under closed-circuit conditions, as with a ring sample or with a permeameter, it is a definite characteristic of the material. If, however, it is determined on a bar sample, for instance, with a small enough dimension ratio to allow some self-demagnetization, the applied ocH_c obviously will be larger the smaller the dimension ratio. It is always larger than the normal H_c value. This characteristic of a magnetic sample is of doubtful value.

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* See Chap. II.

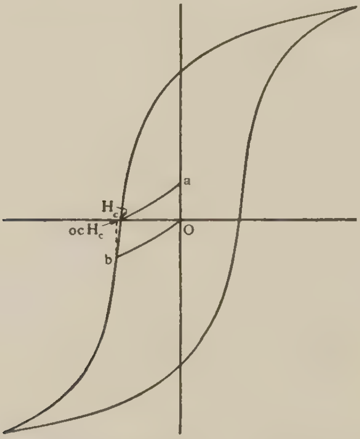

FIG. 44.—Hysteresis loop showing nature of open-circuit coercive force (ocH_c).

Characteristics of Demagnetizing Curve.—Watson[10] has published some very instructive information concerning the demagnetizing curves of permanent-magnet steels in which he shows that Lamont's or Kennelly's law holds for this case as well as for the magnetizing curve, under the condition of homogeneous material. Lamont's law states that the permeability of a steel is proportional to the difference between the saturation density of the steel and the density at the point under consideration. This law as applied to the demagnetizing curve reduces to the following equation:

$$\frac{H + H_c}{B} = a + b(H + H_c), \tag{45}$$

where H and B are the values corresponding to the point in question;

a is the slope of the curve at the point $H = H_c$;

b is equal to $\frac{1}{B_s}$;

B_s is the saturation value of the ferric induction.

Now referring to Fig. 45, the demagnetizing curve $B_rP_1PH_c$ is shown. Horizontal and vertical lines are drawn through B_s, B_r and H_c. Now suppose a horizontal and a vertical line are drawn through any point on the curve such as P_1, giving the points M_1 and N_1. A straight line through N_1M_1 will intersect the horizontal through B_s at O_1. Evershed[7] and Watson[10] have shown that, with homogeneous material, all similar lines obtained from other points on the demagnetizing curve will pass through O_1. They have also shown that if H_c and any other two points on the demagnetizing curve are known, such as B_r and P_2 (it is not essential that B_r be one of these two), by an inverse process B_s and as many points as desired on the demagnetizing curve may be determined. If desired, the curve may be extended to the right of B_r by a similar construction. The point P given by the intersection of the line OO_1 with the curve corresponds to $(B_dH_d)_{\max}$. Watson has also shown that if the points on the

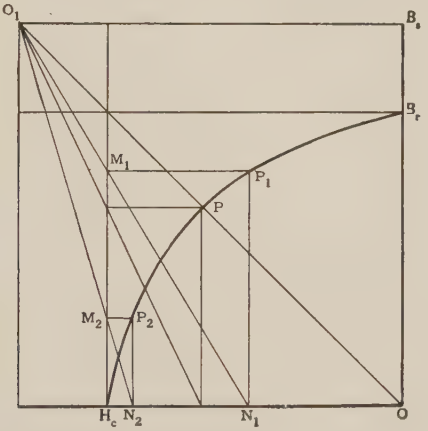

FIG. 45.—Demagnetization curve showing application of Lamont's law.

demagnetizing curve obtained by this graphical construction do not coincide with the curve as obtained experimentally, the material must be nonhomogeneous; just as for the case of the reluctivity curve and nonhomogeneous material, a straight line does not result.*

MAGNET MATERIALS

The various kinds of material which are used for permanent magnets and the field of usefulness of each type of magnetic material will now be considered in detail, in so far as this can be done in view of the rapid changes in the state of the art.

Cast Iron.—This material has been used to a very slight extent, if at all, commercially; but some research work has been done on the subject by Campbell in England and by Pierce in America.[11] The advantages of cast iron are that it is both inexpensive and easily machined. When properly quenched to give the required magnetic properties, it is very hard and brittle. Coercive forces of about 50 gilberts per centimeter can be obtained. This is only slightly less than for carbon steel. The retentivity is, however, much lower than for carbon steel. For magnets with a large demagnetizing coefficient this low retentivity might not be a serious disadvantage. The temperature coefficient is said to be low.

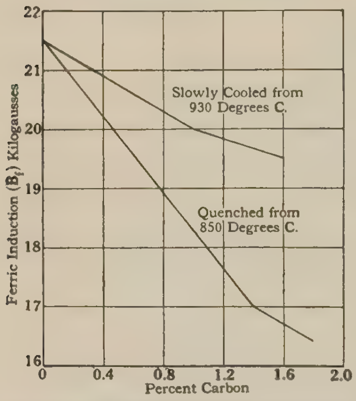

FIG. 46.—Effect of carbon on saturation of iron.

Carbon Steel.—Plain carbon steels are no longer of much importance from the standpoint of permanent-magnet steel, since some of the alloy steels are so much superior; but some consideration of their properties and heat-treatment is worthwhile, as this will make clearer the effects produced by the introduction of the alloying materials. The saturation induction for the iron carbon series is given by Fig. 46 as obtained from data reported by Gumlich. One of the most important factors in producing a satisfactory magnet steel is the heat-treatment and this in turn is intimately connected with the thermal transformation points.

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* See Chap. II.

Figure 47 shows the effect of carbon on these transformation temperatures, as given by Thompson, but with the temperatures modified to agree with more recent experimental results. If a sample of pure iron is heated at a uniform rate, there is a sudden pause in the rise in temperature at 768°C. indicating some change in the state of the material. If the heating is continued, there is another pause at about 909°C., this second pause being much more pronounced. The first point is called the Ac_2 transformation, and the second the Ac_3. Below the Ac_2 point the iron is said to be in the α state, or in the form of ferrite; between Ac_2 and Ac_3 it is called β iron; and above Ac_3 it is termed γ iron. Near the Ac_2 point the material changes from strongly magnetic to weakly magnetic as the temperature is raised, and at the Ac_3 point it becomes practically nonmagnetic. Now, if the sample is cooled from the γ state, the change to β iron occurs at about 898°C. and this is called the Ar_3 transformation. The change to α iron occurs at 768°C. and is known as the Ar_2 point. It will be noted that the Ac_3 point is higher than the Ar_3 point, but that the Ac_2 and the Ar_2 transformations coincide. These temperatures are taken from the work of Burgess at the Bureau of Standards. Recent X-ray studies[12] have shown that α and β irons have the body-centered cubic structure, while the γ iron has the face-centered arrangement, the latter being like nickel and cobalt. As a matter of interest, it may be mentioned that there is still another transformation point at about 1400°C., above which the iron is in the δ form, which has the same structure as α and β irons.

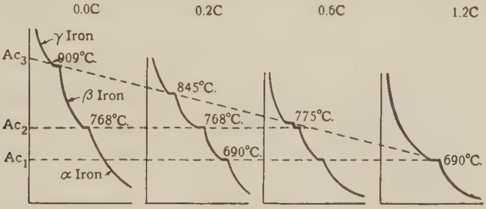

FIG. 47.—Effect of carbon on transformation points of carbon-iron alloys.

Now, when carbon is introduced, as shown by Fig. 47, the transformation points are lowered and a new one appears; namely, the A_1 point at about 690°C. At a carbon content of about 0.35 per cent, the A_3 and A_2 points come together, and at a carbon percentage of 1.2, there is only one transformation; namely, from α iron to γ iron at a temperature of 690°C.

The temperature of the A_1 transformation is affected by the rate of heating or cooling. The Ac_1 point occurs at increasingly higher temperatures as the rate increases, but the change is not very great. With decreasing temperature, however, the Ar_1 point is considerably affected. Even moderate rates of cooling corresponding to the ordinary practice in thermal analysis may lower the point 20 to 30°. According to data by Pilling, the true A_1 point for pure iron for very slow rates of temperature change is about 733 instead of 690°C.

Now, consider again the magnet steels. For pure iron, no heat-treatment will give a satisfactory permanent magnet since the coercive force always will be low. When, however, the carbon content is increased and the material is suitably quenched, the coercive force may become quite high. The coercive force increases with the carbon content. In order to obtain a satisfactory carbon-steel magnet, the material first should be normalized by heating slowly to 850 or 900°C. and cooled in air. It then must be reheated to a point above the Ac_3 range and quenched in water or some other suitable cooling medium before it drops to the Ar_3 point. It must be kept in the quenching medium until the Ar_1 transformation takes place. In order to obtain the best results, the quenching temperature must not be very far above the Ar_3 point. For high-carbon steel, a quenching temperature of approximately 770°C. seems to give the best results. Cyclic changes through the recalescence point before quenching are said to slightly improve the resulting magnetic properties. There seems to be some difference of opinion as to the efficiency of drawing after quenching, but apparently there is a little advantage in drawing to about 220°C. for short magnets and to 260° for long. The best drawing temperature is governed by the relative importance of B_r and H_c; for a large dimension ratio, the former being more important, and for a small dimension ratio, the latter.

After suitable heat-treatment the magnet may be magnetized in a number of ways. If it is of convenient shape, it may be placed in a solenoid through which a heavy direct current is passed for an instant. This current should not be suddenly broken, but first should be reduced gradually to a small value. The time of application of the current is immaterial. If desired, the magnet may be applied to the poles of a powerful electromagnet. If possible, it is desirable to magnetize the magnet in its final position, with pole pieces attached. If the magnet is magnetized by applying it to the poles of an electromagnet, then withdrawn and pole pieces applied, the residual magnetism will be less than if the magnet has the pole pieces attached when the magnetizing force is applied.

The magnetism of a newly magnetized magnet seems to consist of two parts, one stable and one unstable and easily removed by a variety of means. Where constancy is desirable, as in the application to meters, it is essential to remove this unstable portion. If a magnet is allowed to rest at room temperature, its residual magnetism may decrease with time at a gradually diminishing rate for a period of years. For carbon steels, this unstable magnetism may amount to as much as 40 per cent. The maturing or aging process may be hastened by mechanical shock, repeated steaming, continued warming, or partial demagnetization. Some thermal treatment seems to be especially desirable. Heating for 20 hours at 60°C. seems to be as effective from a stabilizing standpoint as steaming for 12 hours, and is said to result in a smaller loss of magnetism. Alternate heating and cooling also seems to be desirable. A partial demagnetization by direct current may be an advantage, but when a magnet has been magnetized without pole pieces and the pole pieces then applied, this demagnetization already has been accomplished. If, under these conditions, a small alternating magnetizing force is applied for a considerable time, the magnetism may increase rather than decrease. Ordinarily, however, the application of an alternating magnetizing force is effective in removing the unstable portion of the magnetism, thus resulting in a decrease in residual magnetism. Mechanical shocks are an aid to stabilization and furnish a ready means of determining the constancy of a magnet. If a permanent magnet is tested for residual induction and then dropped from a height of a foot or two onto a block of wood, the resulting change in residual induction is a good measure of the permanency of the magnet. A recent article by Sheufer gives a good discussion of this subject of magnetic stability.[13]

The effect of a.c. or of reversed d.c. as a means of stabilizing permanent magnets will be clear from a consideration of Fig. 3 (Chap. II). Suppose after magnetizing the residual flux is at *b*. Now if an a.c. magnetizing force is applied of a certain value, the flux will fall to a point such as *c* and the flux will then oscillate between points located approximately as *c* and *e*. After removing the a.c. magnetizing force, the flux will be on some part of this minor loop, the loop being almost horizontal and very thin for permanent-magnet steels. Now, any external demagnetizing force to which the magnet may be subjected will not remove the magnetism from within the boundries of the minor loop *c-e* unless it is of such a large value as to exceed the originally applied a.c. magnetizing force. If it has a sufficiently large negative value, of course, the point *c* (and therefore *e*) will be lowered, thus permanently weakening the magnet. The stabilizing a.c. should be of such value as to exceed any future demagnetizing force which is likely to be applied, but it should be no larger than necessary, since otherwise the magnet will be unduly weakened.

After the application of the a.-c. demagnetizing force, any severe mechanical shock or elevated temperature may lower the loop *c-e*. It will drop slightly with time, anyway, due to the phenomena of aging.

Alloy Steels.—It is stated by Thompson that, in the composition of magnet steels, manganese, titanium, copper, sulphur, and phosphorous should be avoided, while carbon, tungsten, and chromium are very beneficial. Honda and others have recently shown that cobalt effects a profound improvement in permanent-magnet steels and Gumlich states that, in conjunction with cobalt, manganese is of value. So far as known, all good magnet steels must have a fairly high percentage of carbon, 0.5 per cent or more, and the alloying elements act largely to keep this carbon in the hardening state. Tungsten, chromium, manganese, and vanadium, according to Thompson, all function this way and also keep the grain size small. The relative efficiency of these elements is in the order named. According to Gumlich,[14] chromium, and presumably the other above-mentioned elements also, increase the coercive force of pure carbon alloys very little, but slow down the decrease of remanence caused by the addition of carbon. Cobalt, for some reason at present unknown, functions chiefly in increasing the coercive force, but has a comparatively small effect on the retentivity.

Tungsten Steels.—As previously mentioned, up to the time of the World War tungsten steel was used almost exclusively for high-grade electrical measuring instruments and magnetos. There are two types, one containing from 5.5 to 8 per cent tungsten and about 0.5 per cent carbon, and the other from 2.5 to

3.5 per cent tungsten and about 1.0 per cent carbon. The high-tungsten steel is easier to work but is more expensive. In America and England a 3 or a 5 per cent tungsten steel is most common. These alloys usually contain a fraction of 1 per cent of manganese and silicon. Chromium may or may not be present in appreciable amounts, but with high percentages of tungsten it is apparently of little value. Evershed states that the best composition of steel is 5.6 per cent tungsten and 0.73 per cent carbon with possible impurities of perhaps 0.67 per cent, the rest being iron. The carbon is supposed to divide equally between the tungsten and iron, forming WC and Fe_3C.

According to Thompson, high-tungsten steel should be normalized by heating to 900°C., lowered to 750°, held for some time and then cooled. To harden, heat to 950° for not more than 5 minutes, cool to 700° and quench in brine or oil at 20 degrees. Some brands of tungsten steel require higher quenching temperatures, from 770 to 850°C. Tungsten steel should not be tempered. For high-carbon percentages, oil quenching is satisfactory and is less likely to result in cracking.

According to Evershed[7] tungsten-magnet steel may be injured either by ultra-heating or by so-called spoiling.

Ultra-heating effects are the result of heating the material to a high temperature such as 1300°C. (δ state) followed by a fairly rapid cooling. This leaves an appreciable percentage of the material in the γ, or austenitic, state even at room temperature. As shown in Chap. XIX, austenite is practically nonmagnetic. For a 6 per cent tungsten steel, the deficiency in magnetism due to the γ iron may be as much as 16 per cent. A very slow cooling in the region of 700°C. or a liquid-air quenching will convert the γ iron to the α or magnetic state.

Spoiling is the result of prolonged heating between 750 and 1214°C. for 6 per cent tungsten steel. It results in decomposition of the carbides. For this steel the worst temperature is 950°C. Due to this heating there may also be a decarbonization of the surface, thus short-circuiting the magnetic flux by a high-permeability skin. Except for this surface decarbonization, spoiled steel of this type may be recovered largely by heating to say 1300°C. for a short time; namely, above the $\gamma - \delta$ transformation point. Cooling from this temperature, of course, must be at the proper rate over certain regions as explained above in order to avoid the harmful effects of ultra-heating, or a liquid-air treatment may be applied. It is preferable, however, to have the mill practice such that spoiling will not occur; namely, avoid prolonged heating in the danger zone.

To summarize the effect of heat-treatment: In order to be highly magnetic, steel must be in the α state (see Chap. XIX). Also, in order to have a high coercive force, the carbon or carbides must be in solution. The change from the γ to the α state tends to throw these carbides out of solution and thereby give a poorer magnet. It is the function of heat-treatment (quenching and perhaps drawing) first to put the carbides in solution by applying a sufficiently high temperature for a sufficiently long time (in the γ region), and then cool the material at a sufficiently rapid rate to keep the carbides in solution, but still in such a way as to retain as little as possible of the material in the γ state. As pointed out by Evershed, the hardened magnet is in an unstable condition, the carbides tending to go out of solution and enter the crystalline state. Due to the very low mobility of the molecules at room temperature, however, this is an extremely slow process. It does, nevertheless, go on for years, resulting in the well-known aging or weakening of the magnets. It is obvious why a higher temperature hastens the aging process. It is due to the fact that the molecular mobility increases with increasing temperature.

The process of aging tungsten-steel magnets is much the same as for carbon steel. Steaming or a slightly lower temperature for 24 hours is quite effective. It seems to make little difference whether the magnet is magnetized before or after the temperature maturing process.

The H_c value is about 60 or a little higher, and B_r about 10 kilogausses (see Fig. 48). $(B_dH_d)_{\max}$ is a little under 300,000. The temperature coefficient α is about -0.0002, as used in the following equation:

$$M = M_0[1 + \alpha(t_1 - t_0)] \tag{46}$$

where M and M_0 are the magnetic moments at the given temperature and at zero centigrade respectively, and $(t_1 - t_0)$ is the number of degrees centigrade above zero.

Madame Curie reports a Styrian steel containing 7.7 per cent tungsten and 1.96 per cent carbon which, when quenched from 800°C., has a coercive force of 85 gilberts per centimeter, but a retentivity of only about 4.6 kilogausses. This steel, of course, would be of no value for long magnets, but for short magnets, with a small dimension ratio, would show up well, due to its comparatively large H_c.

The chief advantage of tungsten steel over plain carbon steel is that it is more stable. While the maximum available energy of tungsten steel is only a little higher than for carbon steel the former is much less subject to loss of magnetic energy by heating or mechanical shock and is less likely to change with time after maturing. This advantage much more than offsets the difference in price for most applications.

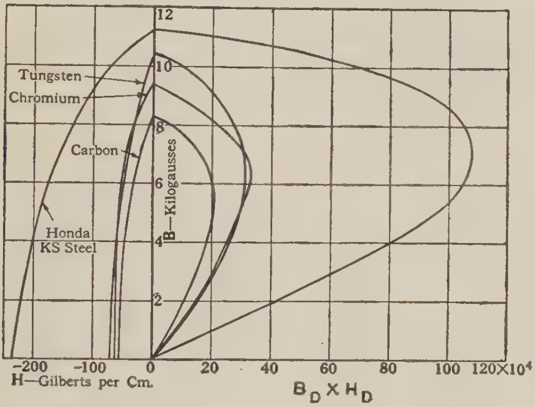

FIG. 48.—Demagnetization curves and $B_d \times H_d$ values for magnet steels.

Chromium Steels.—There probably is being used at the present time a greater tonnage of chromium steel for permanent magnets than all the other magnet steels combined. As far as known, the only real advantage of chromium steel over tungsten for this purpose is that of price, the latter being perhaps 50 per cent higher but this difference is, of course, subject to considerable fluctuation. In America a 2 per cent chromium steel with a little under 1 per cent carbon is quite commonly used. The silicon and manganese are about the same as for tungsten steel. Gumlich[14] reports that alloys containing from 3 to 5 per cent chromium are especially good. Still more recently, he stated that an alloy containing 6.25 per cent chromium and 1.14 per cent carbon is even better.

The proper quenching temperature for chromium steels depends largely on the carbon content and ranges from 750 to 900°C. Gumlich gives 850° as the proper quenching temperature for his high-chromium, high-carbon alloy. He states that oil quenching gives much superior results to water quenching, though water quenching seems to be very satisfactory for the lower chromium alloys. Tungsten steel is apparently not as sensitive to heat-treatment as chromium steel, is less likely to crack, and is less brittle after hardening. The maturing process is about the same as for tungsten steel and the stability is about the same. Dowdell[9] advises drawing at 100°C. for 10 hours (rods 10 by ⅜ inch), then magnetizing and quenching 10 times in ice water from boiling water after holding 5 minutes at each temperature.

The B_r values for chromium steel are about 10 kilogausses, or nearly the same as for tungsten steel. The 2 per cent chromium steels have a little lower H_c values than for tungsten, ranging from 55 to 60 gilberts per centimeter. Gumlich gives values of over 70 for some of his higher chromium steels.

The temperature coefficient of magnetic change is about the same as for tungsten steel. In general, it may be said that, when chromium steel is properly manufactured and carefully heat-treated, it is practically as satisfactory as tungsten steel and due to its lower price its substitution is usually justified.

Molybdenum Steel.—Madam Curie reports a molybdenum steel having from 3.5 to 4.0 per cent molybdenum and 1.25 to 1.75 per cent carbon. With a dimension ratio of 20, the 1.25 per cent carbon alloy had a retentivity of 6.6 kilogausses and a coercive force of 85 gilberts per centimeter. The results were not so good for higher carbon.

Cobalt Alloys.—About 1920 Honda[1] announced the discovery of some new permanent-magnet steels which had remarkably high values of coercive force. These alloys contained large percentages of cobalt. Previously, in 1916, P. H. Brace, of the Westinghouse Company, found that cobalt considerably improved the properties of permanent magnets, but he did not publish his results. The use of these alloys at present is very limited due to the high price of cobalt, but where space and weight are of chief importance these may outweigh the additional cost. Due to the high coercive force, it is possible to obtain a strong magnet even though the dimension ratio is very small. It is quite astonishing for one familiar only with the older types of magnet steels to see a cube of magnetized cobalt alloy lift several times its weight of iron.

Honda's alloy, called KS steel, as originally announced by him had the following composition:

C	0.4 to 0.8 per cent
Co	30 to 40 per cent
W	5 to 9 per cent
Cr	1.5 to 3 per cent

He stated that, after quenching in heavy oil at 950°C., its coercive force would range from 226 to 257 gilberts per centimeter, with corresponding values of B_r of 11.6 to 7.9 kilogausses. Boiling water has very little effect on the residual magnetism, and mechanical shock reduces it only about 6 per cent. For a dimension ratio of 15, this so-called KS steel has 1.8 times the residual induction of tungsten steel, and for a dimension ratio above 20, the residual magnetization is not affected by the ratio. Figure 49 gives a comparison between the magnetization curves and hysteresis loops for chromium and KS-magnet steels. It will be noted that, for these cobalt steels, a much higher magnetizing force is necessary to produce high inductions than is the case for tungsten or chromium steels.

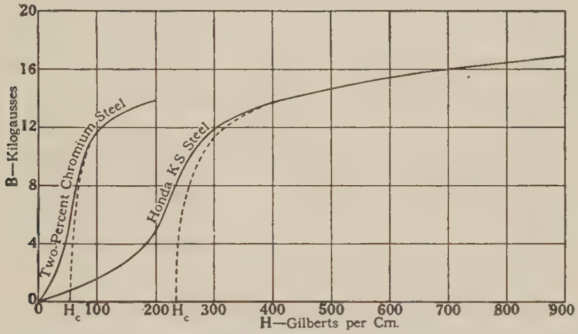

FIG. 49.—Magnetization curves for quenched chromium and for Honda *KS* steel.

Several manufacturers in England and probably elsewhere have put on the market cobalt alloys of this type. In addition to the above-mentioned elements, they usually contain a fraction of 1 per cent of manganese, silicon, nickel, and copper. It has been found that, by the use of smaller percentages of cobalt, less expensive alloys may be made having magnetic properties intermediate between KS steel and tungsten steel. With the best composition at present available, H_c values of nearly 300 can be obtained with corresponding values of B_r of nearly 10 kilogausses. $(B_d H_d)_{\max}$ is almost 1,000,000 at an induction of about 6 kilogausses.

Figure 48 taken from data given by Crapper[15] gives a comparison of the demagnetization curves for various types of heat-treated magnet steels together with the corresponding B_dH_d values. The very great superiority of the cobalt steels is at once evident. By changes in heat-treatment and composition, somewhat higher B_r values may be obtained, but in general, these are, accompanied by lower H_c values.

Cobalt-chromium Alloys.—There have recently appeared on the market so-called cobaltcrom alloys having, according to Kayser,[16] about 1 per cent carbon, frm 9 to 14 per cent chromium, and from 1 to 18 per cent cobalt. These alloys are self-hardening. Their magnetic properties are slightly inferior to those of the best of the Japanese steels, but they are also a little cheaper. Gumlich[17] has shown in a recent article that a certain amount of chromium added to these cobalt alloys is an advantage, and that, to a certain extent, chromium may be substituted for cobalt. He also states that manganese up to 4 or 5 per cent is valuable, but that higher percentages are harmful. The magnetic temperature coefficient is given by him as about the same as for tungsten steel; *viz.*, -2×10^{-4}. Oil quenching is shown to be considerably superior to water quenching. Annealing or drawing is undesirable, since any increase in B_r is offset by a decrease in H_c.

Kayser has given a valuable table (Table V) based on the cost of various types of magnet steels per unit of available magnetic energy. This table can be modified readily at any time to correspond to changes in price of the different alloys. The 6 per cent chromium steel is an alloy reported by Gumlich. The B values

TABLE V.—COST OF MAGNET STEELS PER UNIT OF AVAILABLE MAGNETIC ENERGY

Kind of steel	H_c	B_r	$(B_dH_d)_{max}$	B for $(B_dH_d)_{max}$	Ergs per penny	Cost of 100,000 ergs
2 per cent Cr......	55	10.0	220,000	6.0	49,000	2.04 d†
5 per cent W......	65	10.0	280,000	6.0	41,000	2.44 d
6 per cent Cr......	66.3	12.3	340,000	7.0	36,000	2.78 d
Cobaltcrom (15)*..	220	9.0	700,000	5.5	26,000	3.85 d
Cobalt (36)*......	280	9.5	900,000	6.0	24,000	4.17 d

* Figures in parentheses are percentages of cobalt. † English penny.

are in kilogausses, but the B_dH_d values are for gausses and gilberts per centimeter.

It is evident that from a magnetic standpoint the chromium steel is cheapest. These new higher-priced alloys can therefore find an application only when weight or space is especially important. It might be, also, that for some special purpose the increased coercive force and consequent ability to withstand large demagnetizing forces might be quite useful.

There is one point which should not be overlooked in connection with magnet steels and especially the cobalt steels. The permeability is poor and the incremental permeability* is especially poor; so, if the magnet material is called upon to carry a.c. flux, as is the case in many older types of telephone receivers, it will introduce high reluctance into the magnetic circuit. The incremental permeability even for tungsten steel may be under 10 for a weak signal and for the cobalt alloys much less than this. In designing a polarized apparatus with a permanent magnet and carrying a.-c. flux, the magnetic circuits should be so arranged that the a.-c. flux will not have to pass through the magnet material. This has been done in some of the later types of telephone receivers.

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CHAPTER VI

HYSTERESIS UNDER SPECIAL CONDITIONS

A normal hysteresis loop results when a homogeneous magnetic material has been carefully demagnetized (this is not necessary if the maximum induction is above the point of maximum permeability) and has been subjected to a sufficient number of reversals of equal plus and minus values of magnetizing force to bring the material into a cyclic condition. The normal hysteresis characteristics of materials have been rather fully discussed in Chap. III. This section will be devoted to a consideration of abnormal or special hysteresis characteristics.

Inhomogeneous Materials.—It sometimes happens that a magnetic substance may be made up of two or more components having different hysteresis and permeability characteristics. One case already has been mentioned; namely, that of high-silicon steel having an appreciable layer of scale. These inhomogeneities are especially likely to occur in the case of alloys which may consist of several constituents having different magnetic qualities. The effect on the hysteresis loop caused by such a condition can be shown by obtaining loops on two different homogenous materials for the same maximum induction or the same maximum magnetizing force and then combining the data graphically. It may be assumed that the constituents are magnetically in series or in parallel, the latter condition being the more common. It is quite simple experimentally to determine the result of the parallel condition by first testing ballistically two similar rings of different materials, and then placing one on top of the other and testing them as a unit. Ball[1] has done this for nickel and iron. Figure 50 shows the magnetization curves and Fig. 51 the hysteresis losses. It will be seen that at the lower inductions the curves for the composite sample follow more closely the higher permeability material; but, at the higher inductions, the composite sample gives results which are more nearly a mean. It is usually the case that for different materials in parallel, a composite hysteresis loop will be wide near the top and narrow at low

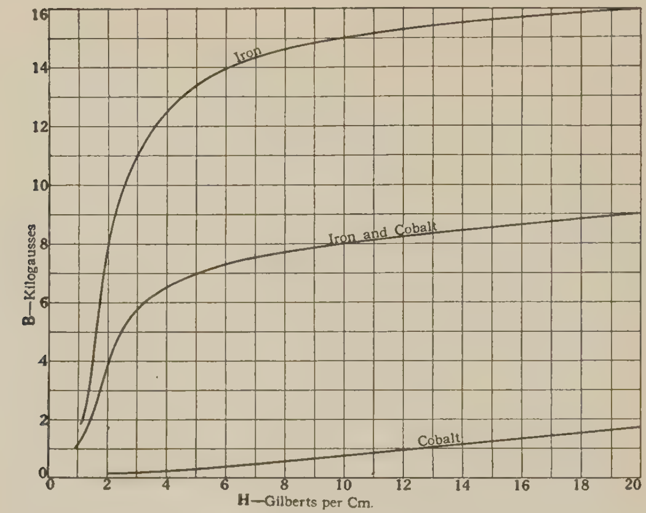

FIG. 50.—Magnetization curves of iron and cobalt tested separately and together.

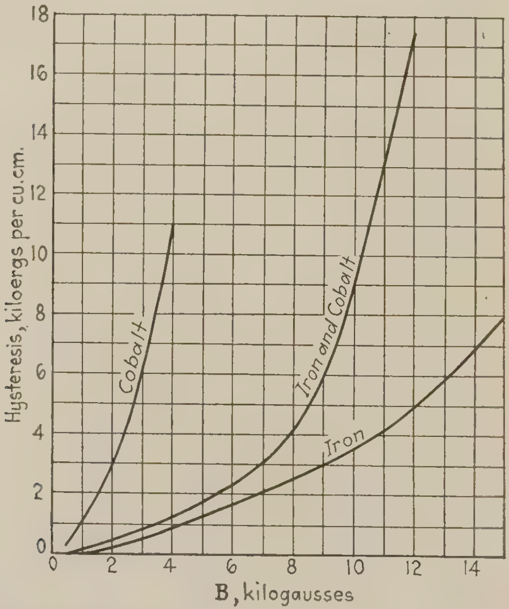

FIG. 51.—Hysteresis losses of iron and cobalt tested separately and together.

inductions.* This is similar to the magnetization curves in that at the high inductions the loop takes on the character of the low-permeability high-loss material and at low inductions of the high-permeability low-loss material. It should be noted that when the induction of the loop is apparently zero it actually consists of a positive flux in the low-permeability substance and an equal negative flux in the high-permeability substance. The reason that the apparent H_c value is small is that only a small demagnetizing force is necessary to produce the required negative flux in the low-loss material.

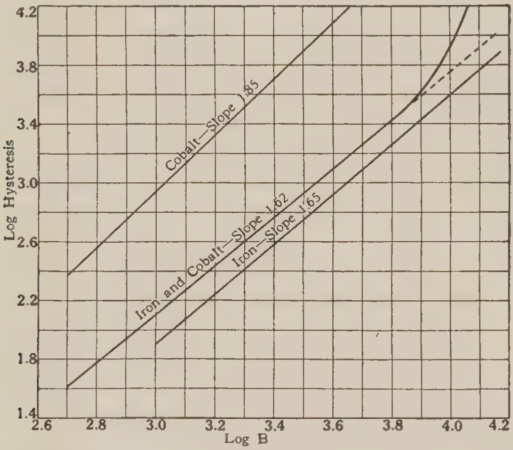

FIG. 52.—Log hysteresis—log B curves of iron and cobalt tested separately and together.

Inhomogeneous alloys will usually show bends in the reluctivity curves when the flux begins to be appreciable in a lower-permeability constituent. The shape of the reluctivity curve and the shape of the hysteresis loop may serve sometimes as means of determining the structure of alloys with respect to both composition and heat-treatment.†

It has already been mentioned that inhomogeneous material may cause a high rate of increase of loss with increasing induction, thus causing Steinmetz's hysteresis law to fail. It is evident that, as the induction in such a material increases, the loss may go up as the 1.6 power, while practically all the flux remains in the high-permeability substance; but, as soon as the flux starts to penetrate the low-permeability higher-loss substance, the rate of increase of loss may be greatly increased as shown by Fig. 52, also due to Ball.

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* See Fig. 12, Chap. III.

† For further details, see Chap. XXV.

Unsymmetrical Hysteresis Loops.—When a magnetic material is subjected to unequal positive and negative values of magnetizing force or to alternating larger and smaller values of the same sign, unsymmetrical or displaced hysteresis loops result. This condition will occur if there is a d.c. component in the magnetizing circuit, either applied directly or as the result of feeding a rectifier from the secondary of a transformer; if there is a pulsating reluctance in a magnetic circuit carrying d.-c. or a.-c. flux; or if a part or the whole of a magnetic circuit consists of magnetized permanent-magnet steel. Finally, if the magnetic circuit has been subjected to a high magnetizing force followed by a low magnetizing force reversed one or more times, the resulting hysteresis loop will be unsymmetrical due to the residual magnetism. Numerous examples occur; the teeth of an induction motor supply, perhaps, the most common example. Again, consider the core of a radio transformer, one of the windings of

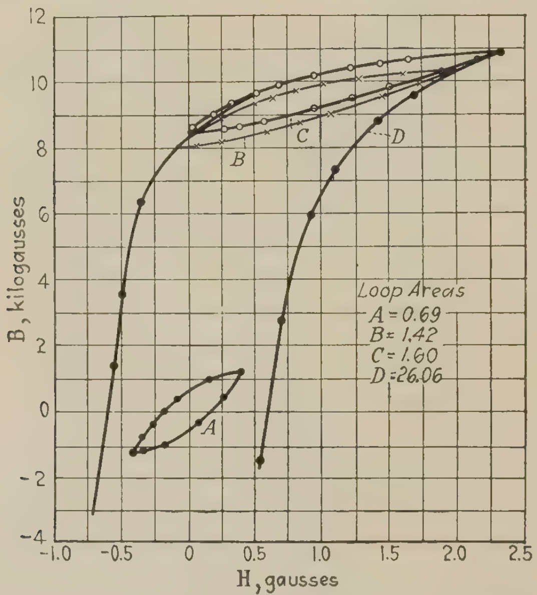

FIG. 53.—Ballistic loops on silicon sheet-steel rings.

Showing the change of shape and area due to displacement. The *B*-amplitude is 2.5 kilogausses.

which is traversed by the d.c. in the plate circuit. The ordinary telephone receiver furnishes a good example. It is seen, then, that this type of hysteresis is well worth consideration.

Figure 53 shows a typical set of these loops where the minor loop at the center has the same induction amplitude as the minor loop at the tip of the major loop. Figure 54 shows a set of loops all having the same B-amplitude, and Fig. 55 a set of loops all having the same mean displacement but different amplitudes. All of these loops were obtained on a large transformer by means of a special fluxmeter.*

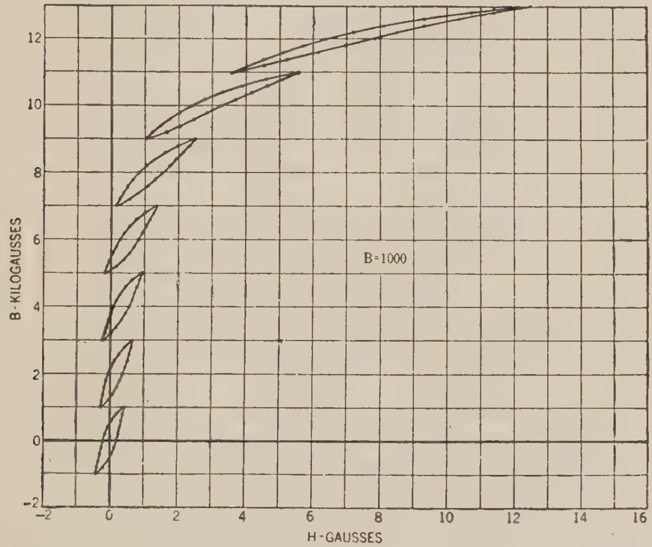

Fig. 54.—Effect of displacement on hysteresis loops having the same B-amplitude (2 kilogausses).

The chief point of interest with regard to this type of hysteresis loop is the fact that for a given B-amplitude the hysteresis loss increases with the displacement from the normal position. The ratio of the loss of the displaced loop to that of the normal loop is termed the displacement factor. Under certain conditions this displacement factor may amount to 10 or more. Ball[3] has derived an equation for the hysteresis loss of unsymmetrical loops, which holds well for comparatively small B-amplitudes, but gives too high losses for large amplitudes:

$$W_{dh} = (\eta + aBm^{1.9})B^{1.6}, \tag{47}$$

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* For further details and illustrations see the *Trans. A.I.E.E.* for 1915.[2,3]

where W_{dh} is the loss of the displaced hysteresis loop;
η is the Steinmetz coefficient;
a is a coefficient depending on the material;
Bm is the mean displacement of the minor loop;
B is one-half the amplitude of the minor loop.

It will be seen that when Bm is zero the function reduces to the usual Steinmetz equation. When W_{dh} is expressed in ergs per cubic centimeter the following constants apply in equation (47) according to Ball:

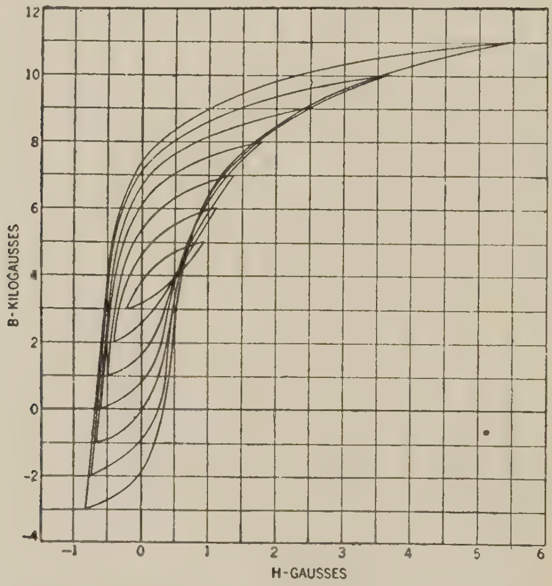

FIG. 55.—Effect of displacement on hysteresis loops having the same displacement (4 kilogausses) but different B-amplitudes.

Material	η	a
Medium-silicon steel....................	1.05×10^{-3}	0.320×10^{-10}
Low-silicon steel........................	1.06×10^{-3}	0.344×10^{-10}

Some very interesting work on displaced hysteresis loops has recently been done in Japan.[4] These tests were made largely under a.-c. conditions on ring samples. In order to eliminate the disturbing effect of eddy-currents, the laminations consisted of 3-mil high-silicon steel sheet. This material had about one-fifth the maximum permeability of 14-mil material of the same composition and about five times the hysteresis loss. Consequently, the specific results will not apply to ordinary commercial material; but, qualitatively, the effects are probably the same. In addition to actual hysteresis data, the Japanese work covers the effect of alternating current on the d.-c. magnetization curve and on the apparent d.-c. hysteresis loop. Also, data are given on the effect of d.c. on the a.-c. magnetizing current for a given *B*-amplitude of the displaced loop.

Figure 5* gives a typical set of curves showing the effect of superposed a.-c. on the d.-c. magnetization curve as reported by Niwa and Asami. These curves should be compared with those of Fig. 6. It will be noted that at low magnetizing forces the a.-c. produces a higher apparent permeability, while at higher magnetizing forces the apparent permeability is greatly reduced. At much higher d.-c. magnetizing forces, the curves would approach each other again. Figure 56 shows the effect of the a.-c. on the apparent d.-c. hysteresis loops.[4] For small d.-c. magnetizing forces, the apparent loop has a higher maximum induction and for high magnetizing forces a lower maximum induction. These loops of Fig. 56 are for small d.-c. magnetizing forces. They were obtained ballistically, with 60 cycles of such a value applied that the induced alternating voltage in a secondary winding

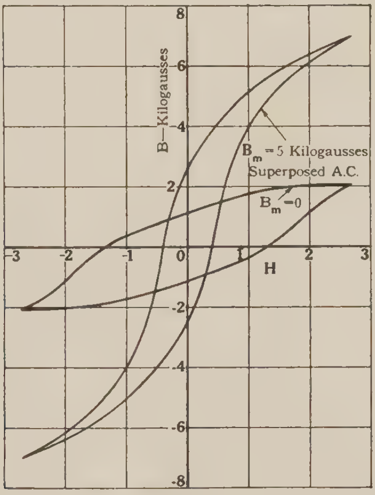

FIG. 56.—Effect of superposed a.c. on apparent hysteresis loop for thin 4 per cent silicon steel.

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* See Chap. II.

indicated a maximum alternating induction of 5 kilogausses. If the a.-c. magnetizing forces are sufficiently high, the hysteresis loop collapses to such an extent that the apparent hysteresis loss is practically zero. The apparent H_c values with the superposed a.c. are always less; but the apparent hysteresis loss may be greater or less depending on the amount of increase of maximum induction.

For the inductions at which most electrical apparatus operates, the superposed a.c. produces a very much decreased apparent fundamental-frequency hysteresis loss as shown by a ballistic test for instance. It might be assumed from this that when a high-frequency flux is superposed on a low-frequency one, the low-frequency hysteresis loss would be largely suppressed. A little consideration will show, it seems, that this is not the case and that the decrease in fundamental hysteresis loss is only apparent. Referring to Fig. 57 let it be assumed that there is a d.-c. hysteresis loop B_mH_c. Now, add an a.-c. magnetizing force to H_m, the sum being H_m'. This will produce a maximum induction B_m' The a.-c. magnetizing force will fluctuate between H_m' and H_a, and the induction from B_m' to a, giving the top minor hysteresis loop as indicated. Now, if the d.-c. magnetizing force is decreased, the minor loop will drop, the left-hand tip following the new major loop B'_maH_c'. The apparent hysteresis loop will now pass through the centers of the minor loops, as indicated by the dotted lines giving an apparent coercive force $H_c(App.)$. The minor loops on the ascending branch of the major loop have been omitted to

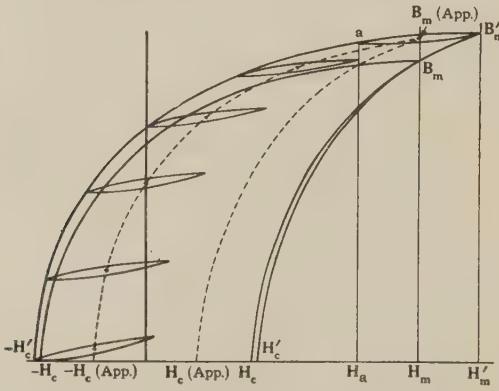

Fig. 57.—Effect of superposed a.c. on apparent hysteresis loop.

avoid confusion. The apparent maximum induction $B_m(App.)$ will lie above or below B_m, depending on the amplitude of the a.-c. magnetizing force. If this analysis is correct, it will be seen that the superposed high frequency not only does not decrease the fundamental hysteresis loss, but may increase it. The magnetization curves and hysteresis loops shown by Niwa and Asami may all be explained by reasoning similar to this.

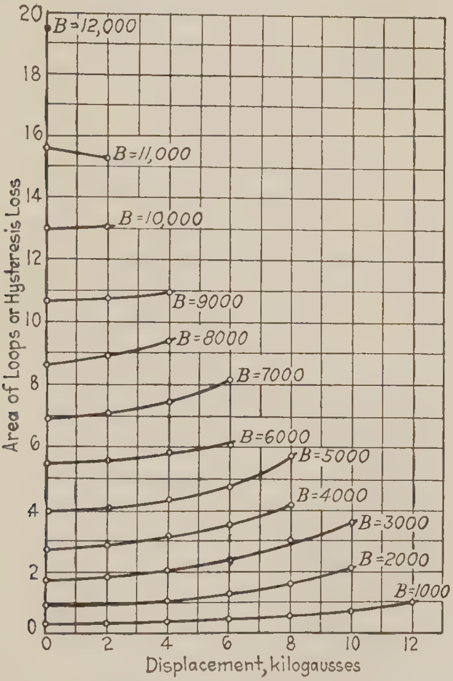

FIG. 58.—Effect of displacement on hysteresis loss—from d.-c. tests.

When the results are given for an anhysteretic magnetization curve with the a.-c. and d.-c. fluxes parallel, the curve is simply the locus of mid-points of a series of displaced hysteresis loops produced by the a.c. Magnetization curves having almost any desired slope may be produced by this means. In the case of the minor hysteresis loops superposed on major loops, the condition being obtained by applying a high-frequency and a low-frequency magnetizing force to the same sample, if by some means the high frequency is supplied from one circuit connected through a wattmeter, and the low frequency through another wattmeter, the low-frequency wattmeter may show a decreased input when the high frequency is applied, corresponding to the apparent major hysteresis loop obtained ballistically with superposed a.-c. (see Figs. 56 and 57). This does not mean, however, that the loss corresponding to loop $B_m' \ H_c'$, Figure 57, does not exist, but that it is supplied partly by the high-frequency circuit.

Figure 58 shows the relation between hysteresis loss and mean displacement of the minor loop for various minor-loop amplitudes. The B values, as given, are for one-half the amplitude of the minor loop. These results were obtained by d.-c. methods on a power transformer, the core of which was made of high-silicon steel. These curves are very similar to the Japanese results obtained by a.-c. methods on thin silicon steel. Figure 59 shows some displacement-factor results obtained by a.-c. methods on commercial electrical sheet. The displacement factor seems to reach a maximum for a certain displacement, and then decreases. Similar results were obtained by Niwa and Asami on the thin sheet. They have also shown that the displacement factor is practically the same whether the minor loop is superposed on the ascending or the descending branch of the major loop. According to these same investigators, the hysteresis loss for the minor loops is an exponential function of the d.-c. magnetizing force, the exponent

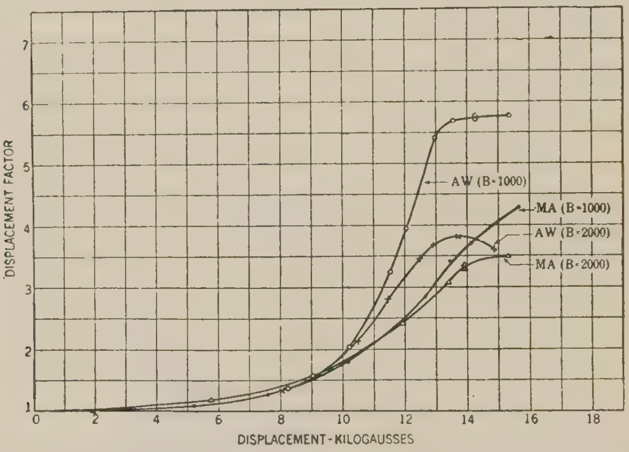

FIG. 59.—Relation between displacement factor and displacement for open-hearth (MA) and silicon (AW) sheet-steel rings—from a.-c. tests.

ranging from 0.4 for a one-half amplitude value of 1 kilogauss, to 0.03 for 10 kilogausses. Finally, they have shown that the root-mean-square alternating-magnetizing current is practically a linear function of the direct current.

The following general conclusions result from these investigations:

1. Superposed a.c. increases the apparent d.-c. permeability for low mangetizing forces but decreases it for high magnetizing forces.

2. For low-induction major loops or small a.-c. magnetizing forces the superposed a.c. increases the maximum induction of the apparent major loop, while for high-induction major loops and large a.-c. magnetizing forces the maximum induction of the apparent major loop is decreased.

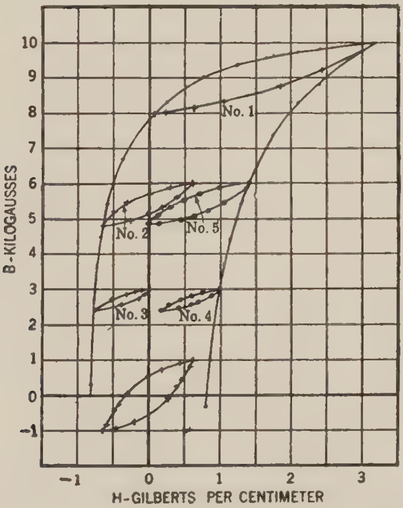

FIG. 60.—Series of minor loops associated with a major loop for 0.0172 inch gage, 1 per cent silicon steel.

The amplitude of displaced loops equals 20 per cent of the displacement.

3. The root-mean-square magnetizing current is practically a linear function of the direct current.

4. For a given amplitude of minor loop, the unsymmetrical loops have a hysteresis loss which increases exponentially with the d.-c. magnetizing force, the exponent approaching zero as the amplitude increases.

5. For a given amplitude of minor loop, the unsymmetrical loops have a hysteresis loss which increases exponentially with the mean displacement, the exponent being about 1.9 for small amplitudes, but becoming

less for large amplitudes until it becomes zero and finally negative for very large amplitudes.

6. The loss of the unsymmetrical loops increases approximately as the 1.6 power of the amplitude over a wide range of mean displacement, tending to become slightly less as the displacement increases.

7. There is a large variation in displacement factor for different materials, and this apparently is not a function of the normal hysteresis, but may be influenced considerably by the permeability.

The preceding discussion does not cover specifically the case of induction-motor teeth where the amplitude of the minor loops is a definite function of the displacement. As a first approximation, it may be assumed that the amplitude is a linear function of the displacement. Figure 60 shows a series of minor loops associated with a given major loop, the amplitude of the minor loops being 20 per cent of the induction of the tip farthest from zero induction. The small loop at the center has the same B-amplitude as the farthest displaced loop. Figure 61 shows the collected results for a series of these loops. These minor loops are

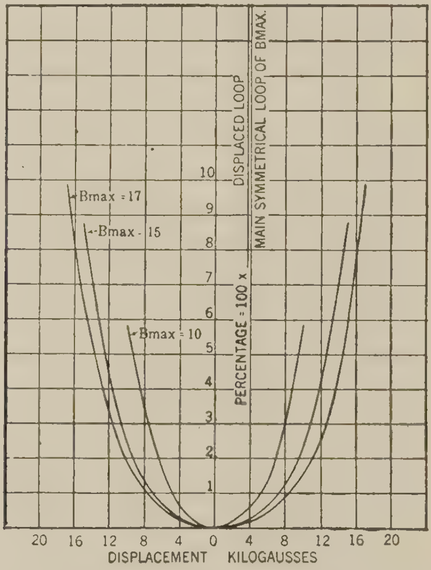

FIG. 61.—Collected results for a series of loops as in Fig. 60.

The ordinates are the percentage hysteresis loss of the displaced loops with reference to the loss of the major loop with which they are associated and the abscissæ the induction of the tips of the loops farthest from zero induction.

all 20 per cent loops and are associated with major loops having maximum inductions of 10, 15, and 17 kilogausses, respectively. Approximately, the same per cent values are obtained for quite different kinds of electrical sheet. In order to apply these results, the hysteresis losses due to the minor loops may be calculated from the following formula:[5]

$$W_{dh} = CKTf, \tag{48}$$

where W_{dh} = watts per kilogram for a given B_m;
C = hysteresis loss in watt-seconds per kilogram per cycle for a major loop having a maximum induction B_m;
K = a constant;
T = teeth per pair of poles;
f = fundamental frequency in cycles per second.

(Tf is, then, the frequency of the tooth pulsations, or minor loops.)

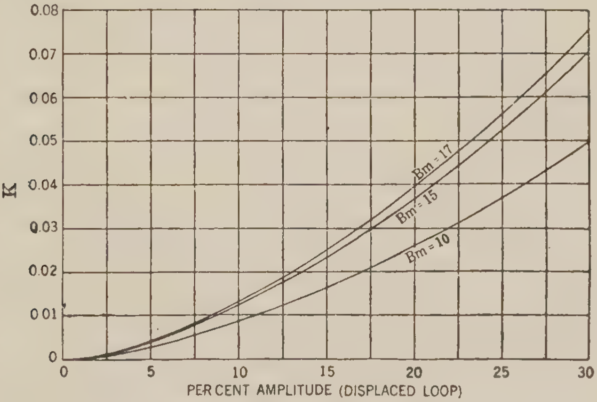

FIG. 62.—Factor K for formula (48) calculated for 1 per cent silicon steel.

Figure 62 gives the constant K plotted against per cent amplitude of the displaced loop for the three major loops. For maximum inductions of over 17 kilogausses, probably no great error will result from using the 17-kilogauss K values.

Provided the thickness of the sheet is not sufficiently great, nor the frequency high enough to produce skin effect, displacement of the hysteresis loop does not affect the eddy-current losses. The eddy losses are a function only of the flux amplitude and may be calculated by the ordinary formulas. If skin effect is appreciable, the eddy losses will be increased by displacement due to the decrease in effective permeability.

Rotating Hysteresis.—Ewing predicted on the basis of his magnetic theory that, when a magnetic material is subjected to a rotating magnetic field, as is the case, sometimes, in the cores of rotating machines, at high flux densities the hysteresis loss would tend to decrease and at very high densities would become zero. A few years later Bailey[6] showed by experiment that, at about 15 kilogausses, the rotating hysteresis loss is about double the corresponding alternating hysteresis loss, and then rapidly decreases with increase of flux density and approaches zero. This was hailed as positive proof of Ewing's theory. A number of experimenters since have made similar experiments with varying results. Moreover, there are certain theoretical considerations which indicate that rotating hysteresis cannot approach zero at high flux densities.

The experimental difficulties are twofold. Unless a spherical or ellipsoidal core is used, the flux distribution varies as the induction is changed, due to the change in permeability; but more important still, there are always present eddy-currents the magnitude of which is hard to determine. The losses due to these eddy-currents are difficult to calculate, and even more difficult is the calculation of their effect on the flux distribution. For these reasons very considerable doubt is thrown on the reliability of any experimental results so far reported. From certain theoretical considerations, moreover, some authorities believe that the hysteresis loss under rotating conditions is the same as for alternating conditions. Due to this uncertainty and to the fact that the laws of rotating hysteresis are not accurately known, while those of alternating hysteresis are quite accurately known, designers of rotating machinery assume that the losses of a rotating core follow the alternating-hysteresis laws. So far as present information on losses in rotating machines is concerned, this seems to be a very satisfactory procedure.

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CHAPTER VII

EFFECTS OF FREQUENCY ON APPARENT PERMEABILITY AND IRON LOSSES

Except at high radio frequencies, true permeability and hysteresis loss per cycle are approximately, at least, independent of frequency. The exceptions will be discussed later. In dealing with this subject three ranges of frequency will be considered; commercial frequencies ranging from 100 cycles per second down; audio frequencies ranging from 100 to 15,000 cycles (15,000 cycles is about the average upper limit for the human ear); radio frequencies ranging from 15,000 cycles up. For commercial frequencies and ordinary laminated material, the permeability is about the same as determined under d.-c. conditions by ballistic or similar means. The hysteresis loss is also normal and may be predicted from the area of the d.-c. hysteresis loop. The eddy-current loss may be calculated by the simple theoretical formula (34) except as already noted for material having large grains, as silicon steel, where the eddy losses are higher than predicted by this formula.* Within commercial frequency limits, this effect is approximately independent of frequency.

Skin Effect.—For audio frequencies a new effect usually comes in—namely skin effect. The presence of this effect, as pointed out by Lloyd,[1] may be detected most readily by plotting the loss in watt-seconds per cycle against frequency, as shown in Fig. 63. For ordinary electrical sheet, this will be nearly a straight line up to approximately 100 cycles, showing that the eddy losses are increasing as the square of the frequency. In the vicinity of this frequency, however, the slope of the curve begins to decrease and it is at this point that skin effect begins to become appreciable. Skin effect is merely the result of the counter m.m.f. or damping effect of the eddy-currents. The damping effect is greatest, of course, at the center of the cross-section of the sheet. This means that the flux at the center of the sheet is less than it is at any other portion of the cross-section

* See Chap. III.

and gradually increases toward the surface until at that point the effective m.m.f. is equal to the applied m.m.f. For a given m.m.f., skin effect produces three results due to this nonuniform distribution of flux:

1. The eddy-currents are less than if skin effect were not present, because there is less effective flux to generate them; or, it may be considered that the mean length of the eddy-current paths has been increased. This results in decreased eddy-current losses over those which would otherwise occur.

2. The hysteresis loss is less. It is evident that since the mean flux is less the hysteresis loss will be less.

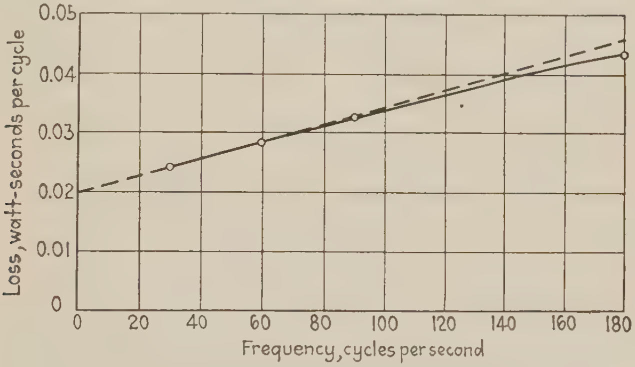

Fig. 63.—Variation of total loss per cycle with frequency. For 27-gage transformer sheet at 5000 gausses.

3. Since the total flux is less, the effective permeability is less. It may be noted also that toward the center of the material, the eddy-currents lag more and more in phase.

Now, for the same mean value of flux density, the conditions will be a little different. The eddy loss will be still less than if skin effect were not present; but, of course, not as much less as for the same values of external magnetizing force. The hysteresis loss, however, will be greater for this reason: hysteresis loss increases faster than the first power of the flux density; therefore, the portion of the material which has its induction above the average will have its loss increased to a greater extent than the portion which has less induction than normal will have its loss decreased. The following general law covers this case: when a magnetic circuit is subjected to a nonuniform magnetic flux the hysteresis loss will be greater than if the circuit were subject to the same average uniform flux. The effective permeability will be less, in general, than when there is no skin effect.

Provided constant permeability is assumed, it is possible to derive theoretical formulas for calculating effective permeability and losses when skin effect is appreciable. Steinmetz and J. J. Thomson have calculated such formulas,[2] giving also the effective penetration of the flux. These formulas hold both for audio and radio frequencies. J. J. Thomson's formula for eddy-current losses as given by Russel* is as follows:

$$W_e = 0.6332\frac{m\rho H^2}{t} \times \frac{\sinh mt - \sin mt}{\cosh mt + \cos mt}. \tag{49}$$

Where $W_e =$ watts eddy loss per cubic centimeter of material;

$m = 1.99 \times 10^{-4}\sqrt{\frac{\mu f}{\rho}}$;

$\rho =$ resistivity in ohm-centimeters;

$\mu =$ permeability $\left(\frac{B}{H}\right)$;

$f =$ frequency in cycles per second;

$H =$ magnetizing force in gilberts per centimeter;

$t =$ thickness of sheet or plate in centimeters

For low frequencies or thin plates where skin effect is negligible, this reduces to formula (34) by substituting B for μH. For thick plates or high frequencies, when mt is greater than π, formula (49) reduces to:

$$W_e = 0.1258 \times 10^{-3}\frac{H^2}{t}\sqrt{\mu f \rho} \tag{50}$$

If the loss in watts per kilogram is desired; it may be obtained by multiplying the loss in watts per cubic centimeter W_e by $10^3/d$, where $d =$ density (7.7 for low-silicon steel and 7.5 for high-silicon steel).

More recently Latour[4] has derived similar formulas from somewhat different considerations, which were calculated in connection with radio problems, but are equally applicable to audio frequencies. These formulas cover not only the condition of a given magnetizing force, to which Russel's formulas are limited, but also the condition of the same average induction, which is often the more convenient assumption. Latour's formulas include hysteresis as well as eddy losses; with some slight modifications they are as follows:

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* For a more complete discussion of these effects and convenient formulas, see Russel.[3]

$$W_e = \frac{\pi^2 f^2 t B_{\text{app}}^2}{2m\rho 10^{16}} \times \frac{\dfrac{\sinh m\alpha t}{\alpha} - \dfrac{\sin m\beta t}{\beta}}{\cosh m\alpha t - \cos m\beta t}. \quad (51)$$

$$W_h = \frac{\pi^2 f^2 t \sin \tau B_{\text{app}}^2}{2m\rho 10^{16}} \times \frac{\dfrac{\sinh m\alpha t}{\alpha} + \dfrac{\sin m\beta t}{\beta}}{\cosh m\alpha t - \cos m\beta t}. \quad (52)$$

$$W_e + W_h = \frac{\pi^2 f^2 t B_{\text{app}}^2}{2m\rho 10^{16}} \times \frac{\alpha \sinh m\alpha t - \beta \sin m\beta t}{\cosh m\alpha t - \cos m\beta t}. \quad (53)$$

When the *sinh* and *cosh* terms approach the same values, namely, when $m\ \alpha\ t$ exceeds π, these formulas reduce to the first term after the equality sign. The symbols are the same as for (49) with the following additions:

W_h = watts hysteresis loss per cubic centimeter of material,
B_{app} = apparent or mean induction in gausses;
$\alpha = \sqrt{1 + \sin \tau}$;
$\beta = \sqrt{1 - \sin \tau}$;
$\sin \tau = \eta + 4\mu$;

$$\eta = \frac{W_{\text{ergs}}\ (hyst)}{B^2_{\max}} = \frac{W_h \times 10^7}{f B^2_{\max}}.$$

The apparent or effective permeability may be obtained as follows:

$$\mu_{\text{app}} = \frac{2\mu}{mt\sqrt{2}} \sqrt{\frac{\cosh m\alpha t - \cos m\beta t}{\cosh m\alpha t + \cos m\beta t}}. \quad (54)$$

When the laminations are thick enough or the frequency high enough that the *sinh* term is nearly equal to the *cosh* term, the eddy losses are proportional to $\dfrac{f^2 t}{m\rho}$ and the hysteresis losses to the same value times τ. This condition is reached for 0.0172-inch 1 per cent silicon steel at frequencies of the order of 500 cycles. Now, under these circumstances, if constant permeability can be assumed, the eddy losses vary as follows:

W_e varies as $f^{1.5}$, t, $\mu^{-0.5}$ and $\rho^{-0.5}$.

Similarly, the hysteresis loss varies as follows:

W_h varies as $f^{1.5}$, t, $\mu^{0.5}$ and $\rho^{-0.5}$.

For the condition of no skin effect, referring to formula (34) it will be seen that the conditions are rather different; thus:

$$W_e \text{ varies as } f^2,\ t^2 \text{ and } \rho^{-1}.$$

Theoretically, the eddy loss is independent of permeability. The hysteresis loss is, of course, independent of all these variables except the frequency.

These formulas would give correct results if permeability were a constant, but, due to the fact that permeability varies with induction, the calculated results using these or similar formulas are often quite different from the actual test values.

Recently Rosenberg[5] has published a method of calculating eddy-current losses giving much simpler formulas based on certain approximations. They hold only when it can be considered that the skin effect is so large that the flux is confined to a surface layer less than one-half the thickness of the magnetic material. Rosenberg assumes that, when skin effect is large, all of the flux is confined to a certain limited area extending from the surface inward to a distance a, Fig. 64, where t is the total thickness of the sheet or plate. The flux is assumed to be of uniform density over the section a. This is not far from the truth for high magnetizing forces, as will be seen from a consideration of the shape of the ordinary magnetization curve. On this assumption, the eddy-currents will vary uniformly from a maximum on the surface to zero at the inside edge of the section a, and the eddy losses, since they vary as the square of the current, will vary parabolically from a maximum at the surface to zero at the inside edge of a.

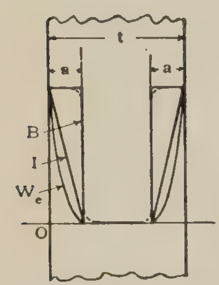

FIG. 64.—Assumed distribution of flux and current across section of sheet under conditions of large skin effect.

On these assumptions Rosenberg has developed the following eddy-loss formula for solid material of any cross-section where the magnetizing force is known and the total flux unknown. It will be noted that, in the Latour formulas given above, the total flux was known, but the magnetizing force was unknown.

$$W_e = 1.189 \times 10^{-4}\sqrt{\rho f H_{\text{cm}}{}^3 B}. \tag{55}$$

Where W_e = eddy loss in watts per square centimeter of surface;
ρ = resistivity in ohm-centimeters;

H_{cm} = magnetizing force in maximum ampere-turns per centimeter;

B = induction in gausses corresponding to H_{cm} from the d.-c. magnetization curve.

If the alternating magnetizing current is given, H_{cm} is obtained by multiplying the a.-c. ampere-turns per centimeter by $\sqrt{2}$ (sine wave assumed), or

$$H_{\text{cm}} = \frac{I_{\text{rms}} \times N \times \sqrt{2}}{\text{Length of magnetic circuit in centimeters}}.$$

where I_{rms} = root-mean-square value of alternating current,

N = number of primary turns.

The depth of flux penetration in centimeters is given by the following:

$$a = 5640\sqrt{\frac{\rho H_{\text{cm}}}{fB}}. \tag{56}$$

For uniform flux density over the whole section of the material (negligible skin effect),

$$W_e = 0.82 \times 10^{-16}\frac{f^2B^2t^2}{\rho} \text{ watts per square centimeter.} \tag{57}$$

This formula gives results identical with those given by formula (34). For bars of circular cross-section, the induction may be considered uniform over the section when the radius in centimeters is not greater than

$$r_{\text{cm}} = 8000\sqrt{\frac{\rho H_{\text{cm}}}{fB}}.$$

It is interesting to compare formulas (55) and (57), and note how the eddy losses vary with the different factors when the flux is uniform and when it is confined to a surface layer. This comparison is on a basis of equal magnetizing forces and not for equal total flux as was the case for the previous comparison. For uniform flux,

$$W_e \text{ varies as } f^2,\ B^2 \text{ and } \frac{1}{\rho};$$

and for flux confined to a surface layer by skin effect,

$$W_e \text{ varies as } f^{0.5},\ B^{0.5} \text{ and } \rho^{0.5}.$$

It will be seen that, after the material becomes thicker than $2a$, the loss per unit surface area is independent of the weight or volume of the iron. Another thing of importance is that under these conditions the loss increases with the resistivity, rather than decreasing as is the case with thin material carrying uniform flux. This means that it often may be a mistake to use high-resistivity material for the frames and end bells of machines with the object of reducing eddy-current losses. It should be noted that the induction indicated is that corresponding to the magnetizing force and is not the mean induction for the whole section. In other words, if laminated material is of such a thickness that formula (55) applies, the apparent induction may be double, but, due to the shape of the magnetization curve, the surface induction may be much more than doubled for low inductions, or much less than doubled for high inductions.

It should be noted that there is a certain range between the application of formulas (55) and (57), where $2a$ is greater than the thickness of the material, when it is not safe to use either formula. Latour's formulas show no such discontinuity.

For the case where the magnetizing force at the surface is not known but the mean induction is known, Rosenberg uses the following formula:

$$Ba = 5640\sqrt{\frac{\rho}{f}B\,H_{\text{cm}}}. \qquad (58)$$

The total flux $2Ba$ is equal, of course, to $B_{\text{app}} \times A$ where B_{app} is the apparent induction and A is the total cross-section of the iron. The product BH can then be calculated and B and H then obtained from the d.-c. magnetization curve for the material. It should be noted that Ba is obtained thus:

$$Ba = \frac{B_{\text{app}} \times t}{2},$$

where t = thickness of sheet in centimeters.

Again, it is sometimes convenient to calculate a from an assumed permeability instead of from the B and H values. Formula (42) then becomes,

$$a = 5030\sqrt{\frac{\rho}{f\mu}}. \qquad (59)$$

Rosenberg does not mention the subject of hysteresis losses. On the basis of his assumptions, however, it is possible to obtain a rough estimate of these losses under conditions of large skin effect. If the specific hysteresis loss for a material corresponding to B is multiplied by the volume of the section a this loss is obtained. The formula is as follows:

$$W_h = W_{10/h} \times \left(\frac{B}{10}\right)^{1.6} \times f \times \frac{2a}{t}; \qquad (60)$$

where W_h = hysteresis loss in watts per kilogram for the given frequency;

$W_{10/h}$ = specific hysteresis loss of the material in watt-seconds per kilogram per cycle for an induction of 10 kilogausses;

B = surface induction in kilogausses;

a = depth of flux penetration in centimeters, calculated from formula (56) or (59);

t = thickness of sheet in centimeters.

In general, this method gives losses which are less than those obtained by Latour's formula (52).

Reliability of Formulas.—In the use of Latour's formulas there is the difficulty of choosing the proper value of effective permeability and the fact that the formulas are complicated, involving considerable time for the detailed calculations. The Rosenberg formulas are simple and easy to use, but require some judgment in their application and even then may be subject to large errors. Referring to formula (55), it will be seen that great care is necessary in estimating or measuring H. However, with a sine-wave current and a thick material, the eddy-loss calculations will not be far off. The hysteresis losses as calculated by formula (60) will be much too low, due to the fact that the flux is high enough in the interior of the material, beyond the section a, to produce considerable losses. Again, if the surface inductions are high, the hysteresis losses will increase much faster than the 1.6 power of the induction. If the specific loss of the material at the induction is known, of course, approximate corrections may be made.

If, however, the apparent induction is given instead of the maximum exciting current, the matter is open to large errors for several reasons. If the skin effect is large, the surface inductions are high even for low apparent inductions, and either the magnetizing current will be much peaked or the flux wave will be peaked, or both, depending on the conditions. In either case, it is difficult to estimate accurately the maximum values of B and

H for use in the Rosenberg formulas. The more serious difficulty seems to be that these formulas neglect a small but by no means negligible flux in the inner portion of the sample, causing the value of B as obtained from formula (58) and the d.-c. magnetization curve of the material to be somewhat higher than the actual value; and, at high inductions, this means a much higher value of H than the true value, due to the flatness of the magnetization curve at high inductions. For instance, a 1 per cent error in estimating the maximum induction at about 16 kilogausses may mean a 15 to 20 per cent error in estimating H. The loss, moreover, is proportional to the maximum induction and the 1.5 power of H_{max}. It is evident that a small error in estimating B will result in a large error in the loss calculations.

These formulas bring out clearly a point which is often not realized; namely, as pointed out above, eddy-current losses may increase or decrease with increasing resistivity. Due to the fact that, with no skin effect, eddy-current losses are inversely proportional to the resistivity, it is often assumed that this is the case under all circumstances. For a given magnetizing force at the surface, according to theory, the eddy losses vary directly as the square root of the resistivity provided a is less than one-half the thickness of the material. For thinner sheets or plates, or for lower frequencies, the effect of resistivity is somewhere between these extremes. The reason that eddy losses for large skin effect increase with the resistivity is, of course, that a, or the effective depth of penetration of the flux, increases as the square root of the resistivity. This increased depth of penetration more than counterbalances the effect of increased resistance to the eddy-current paths. Now, if the case of the effect of resistivity on eddy losses is considered for the same total flux or mean induction instead of for a given magnetizing force, it is found that the losses vary inversely as the square root of the resistivity. This is due to the fact that for the same mean induction the effective thickness a is less for the low resistivity material and therefore the magnetizing force is higher. For the region where permeability changes quite rapidly with induction the effect of resistivity on eddy losses may depart considerably from the inverse square law.

The Rosenberg formulas, though probably giving less reliable results than the Latour formulas, have one important advantage in that they are applicable to material of any cross-section or shape. The Latour formulas, on the contrary, can be applied only to material having a rectangular cross-section with one cross-sectional dimension much greater than the other; namely, sheets and plates.

Experimental Losses.—Due to the uncertainties of calculation, reliable high-frequency loss values can be obtained only by test. This applies to audio as well as to radio frequencies. Figure 65 shows some calculated hysteresis and eddy-current losses for 0.0172-inch 1 per cent silicon steel, assuming various values of permeability for a range of frequencies from 0 to 3000 cycles per second. There is included a test curve obtained on a sample of this material which illustrates the difficulties of calculation. It should be noted that at low frequencies the eddy losses are much higher than the calculated results, no matter what permeability is assumed. This effect has been mentioned* and is intimately connected with the grain structure.

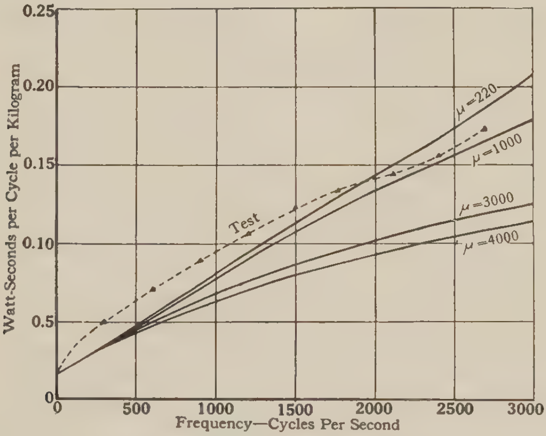

FIG. 65.—Variation of combined hysteresis and eddy losses with frequency.

Comparing results calculated by Latour's formulas assuming various permeabilities, with those obtained by test, for 0.0172-in., 1 per cent silicon steel, at an apparent or mean flux density in the sheet of $B_m = 6$ kilogausses.

Figure 66 shows the effective permeability as obtained by test for 0.065-inch bessemer sheet steel for the same range of frequencies and for various mean inductions. Table VI shows the calculated hysteresis and eddy losses and also the effective permeability for this same material as compared with the test values for a maximum induction of 6 kilogausses. It will be noted that the maximum permeability by ballistic test is 1400 and that a value of 1000 is assumed. It also will be noted that the calculated and test losses check fairly well, but the effective permeability does not. A little consideration will show that, although the direct-current permeability is known, it is difficult to choose a mean value of permeability to use in the formulas. It will be seen that where skin effect is large, instead of distributing itself as would be the case if the permeability were constant the flux actually assumes quite a different distribution. If the mean induction is sufficiently high, the skin effect will so increase the flux toward the surfaces of the sheet that the inductions will become quite high and therefore the permeability quite low. Due, however, to this lower permeability, the flux will not be as concentrated near the surface as would otherwise be the case. In other words, if the inductions are high enough, this change in permeability will tend to keep the flux distribution more uniform with reference to the cross-section of the sheet. If the mean induction is considerably below that corresponding to maximum permeability, of course, the opposite will be the effect for moderate skin effects.

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* See Chap. III.

Table VI.—Losses and Permeability of 0.065-inch Bessemer Sheet Steel at Various Frequencies

Maximum flux density $B_m = 6$ kilogausses; $\mu_m = 1400(B_m = 6)$; μ (assumed) $= 1000$; $\eta = 1.028 \times 10^{-4}$

Cycles per second	Watts loss				Effective permeability	
	Calculated			Test W_t	Calculated μ_{eff}	Test μ_{eff}
	Eddy W_e	Hysteresis W_h	Total W_t			
60	4.85	3.28	8.13	7.7	650	
300	69.8	28.6	98.4	92	289	588
1200	571	235	806	840	147	252
1800	1050	433	1483	1600	120	197
2700	1910	787	2697	3000	98	152

With this explanation, the curves of Fig. 66 can readily be interpreted. The induction corresponding to maximum permeability for this material is about 6 kilogausses. For low frequencies and inductions below 6 kilogausses, therefore, the effective permeabilities are lower than the maximum. Since this material is quite thick, however, even at fairly low frequencies the 3-kilogauss permeabilities become highest. For thinner material and higher frequencies, a set of curves very similar to those of Fig. 66 would be obtained.

It might be thought that with these low effective permeabilities the power factor of an iron load under these high-frequency conditions would be low. For ordinary laminated material over commercial ranges of thickness and over a wide range of frequencies, however, a power factor of from 80 to 90 usually results.

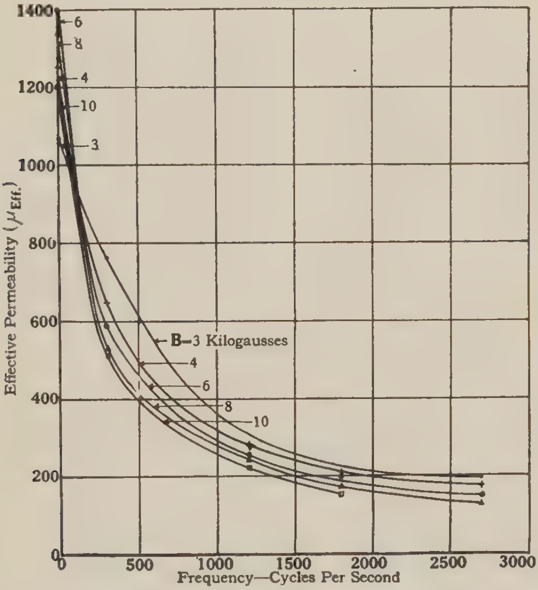

FIG. 66.—Effective permeability as obtained by test for 0.065-inch bessemer sheet steel at constant apparent inductions and varying frequency.

This is because of the fact that the losses go up so rapidly with the frequency.

When the total losses for commercial electrical sheet are plotted on double-log paper against frequencies well within the audio range, slopes varying from a little over 1 at the lower frequencies to from 1.6 to 1.7 are obtained. The exponent does not come much nearer to 2 for the highest frequencies in this range, due to the fact that the hysteresis loss is quite an appreciable portion of the whole loss and because skin effect increases with frequency.

TABLE VII.—EXPONENTS OF TOTAL LOSS AGAINST MEAN INDUCTION

Kind of steel	Gage, inches	Frequency in cycles per second							
		30	60	300	800	1200	1800	2200	2700
1 per cent silicon......	0.018	....	....	1.74	1.86	1.86	1.89	1.89	1.90
4 per cent silicon......	0.015	1.72	1.73	1.70	1.85	1.82	1.81	1.95	2.00
2.2 per cent silicon......	0.015	1.69	1.69	1.69	1.85	1.82	1.90	1.97	1.95
2.2 per cent silicon......	0.034	1.79	1.89	1.92	2.08	2.08	2.03	2.11	2.11
2.2 per cent silicon......	0.076	1.79	1.91	2.08	2.15	2.11	2.18	2.16	2.27
Bessemer...............	0.028	1.62	1.70	1.84	1.89	1.92	1.89	1.92	1.97
Bessemer...............	0.065	1.82	1.86	2.10	2.26	2.10	2.03	2.21	2.24
Bessemer...............	0.131	1.95	2.07	2.35	2.38	2.26	2.30	2.30	2.34

The relation between total loss and induction is shown by Table VII. These exponents are not altogether consistent, due to small experimental errors. It will be noted that, for the thicker materials and the higher frequencies, the loss exponents show that the total iron losses increase faster than the square of the induction. This is because the flux is greatly concentrated near the surface of the sheets with resulting high inductions. For high flux densities, it is known that hysteresis loss increases faster than the square of the induction, which accounts for the results in Table VII.

These results will be found of value when considering audio-frequency transformers and losses in the teeth of rotating machines. In the case of the transformers when used with three-electrode tubes, the problem is often complicated by the presence of the unidirectional-plate current, thus producing displaced hysteresis loops. There are similar effects in the case of the teeth of rotating machines. Under these circumstances, skin effects should be estimated from the effective or incremental permeability rather than from the ordinary permeability.

Qualitatively, the same sort of results will be obtained for radio frequencies and thinner materials as have been presented for thicker materials and audio frequencies.

High-frequency induction furnaces and trans-atlantic telegraphy make use of frequencies from say 5000 to 50,000 cycles per second. Five-mil 4 per cent silicon steel is especially suitable for this range of frequencies for the cores of generators and transformers. Figure 67 shows the hysteresis and eddy-current losses for this class of material plotted against induction, and Fig. 68

shows the same data plotted against frequency except that in the latter figure the hysteresis and eddy losses are not separated.[6]

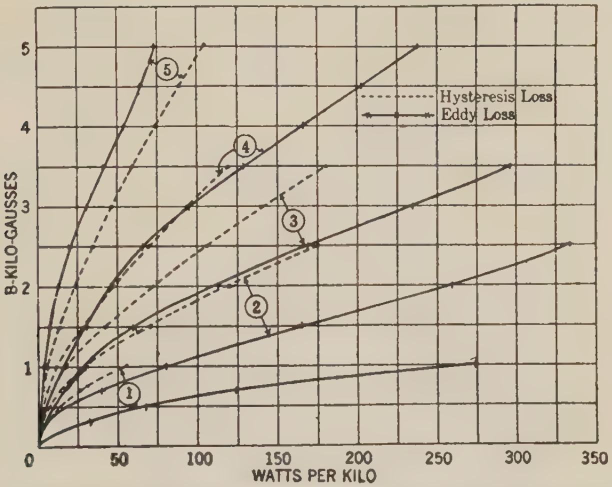

Fig. 67.—Hysteresis and eddy losses in 5-mil, 4 per cent silicon steel at constant frequency and varying maximum induction.

1. 48,800 cycles. 2. 25,000 cycles. 3. 15,100 cycles. 4. 10,000 cycles. 5. 5000 cycles.

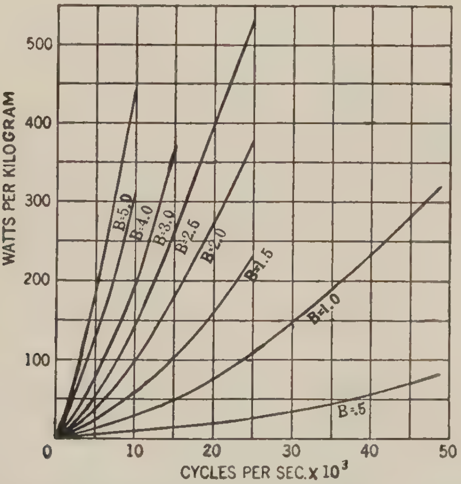

Fig. 68.—Combined hysteresis and eddy losses in 5-mil, 4 per cent silicon steel at constant maximum inductions and varying frequency.

Figure 69 shows the r.m.s. ampere-turns per centimeter plotted against maximum induction for a number of frequencies. The skin effect for this material and range of frequencies is comparatively small. The eddy losses increase at a rate somewhat less than the square of the frequency and induction. These loss results were obtained by a double calorimeter method and the source of high frequency was a tungsten arc oscillator. It is believed that the test results are accurate to plus or minus 5 per cent.

For this range of frequencies and material, the hysteresis and eddy losses are of the same order of magnitude. For higher frequencies, it would pay to use thinner material in order to reduce the eddy losses. The effect of the thinner gage is counterbalanced to some extent, however, by the fact that the thinner material has higher hysteresis losses and, due to scale and the necessary insulation, the space factor is poorer. The 5-mil steel here considered had a hysteresis loss of about double that to be expected for 14-mil sheet of the same composition, and a space factor of about 0.75, as against 0.90 for the thicker steel. By taking all the known factors into account, it is possible to make a fairly reliable estimate of the hysteresis and eddy losses to be expected for other kinds and thicknesses of material.

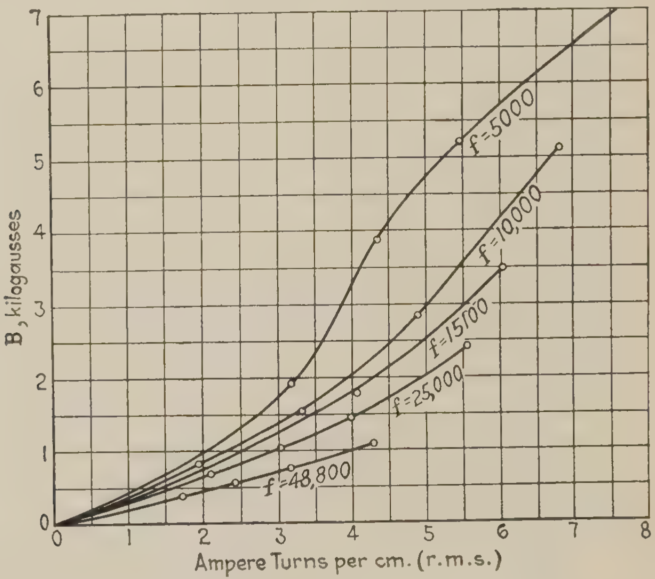

FIG. 69.—Maximum induction in 5-mil, 4 per cent silicon steel.

Some years ago Alexanderson presented some data on the magnetic properties of iron up to frequencies of 200,000 cycles.[7] Up to that time there was considerable doubt as to whether or not the permeability and specific hysteresis loss of iron was the same at these frequencies as at commercial frequencies. This investigation conclusively proved that, when due allowance was made for skin effect, there was no essential difference.

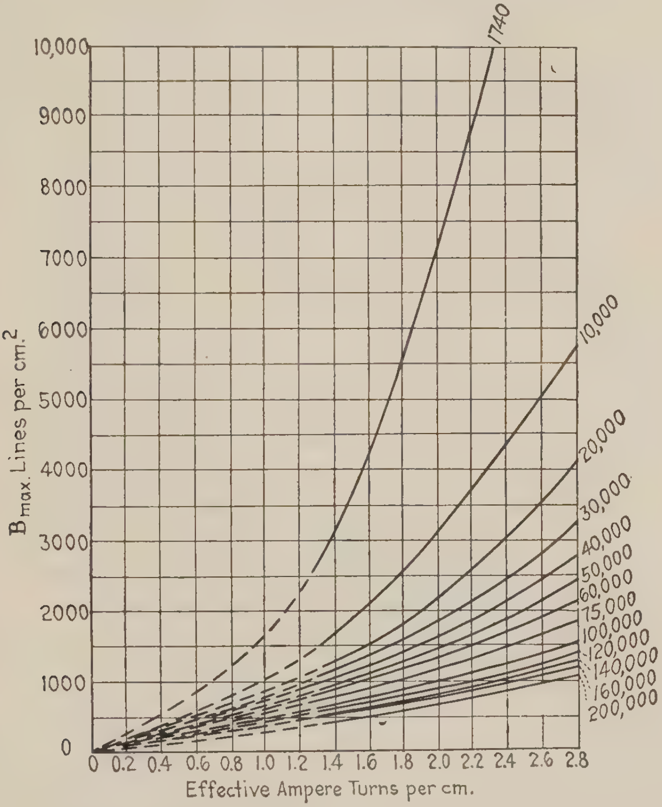

FIG. 70.—Variation of apparent induction with effective ampere-turns at different frequencies.

The high-frequency current for these tests was supplied from a high-frequency alternator, and the magnetic properties measured by means of a hot-wire ammeter and voltmeter with the circuit containing the sample arranged for resonance. The iron itself was a soft iron strip 3 mils thick and 0.75 inch wide. Figure 70 shows the relation between effective ampere-turns per centimeter and apparent induction for various frequencies. Figure 71 shows the relation between effective ampere-turns per centimeter and watts per cubic centimeter for various frequencies. Figure 72 shows the core loss at constant apparent induction and varying frequency for several inductions. The power factor is high, as was the case for the thicker material and audio frequencies. The average permeability of this material at low frequencies was 2250 while at 200,000 cycles due to skin effect it was only 180. This gives an effective flux penetration of 0.0003 centimeter (0.12 mil). The skin effect of this material is much greater than for the same thickness of high-silicon steel due to its much lower resistivity. In order to convert the losses given in the above curves to watts per kilogram, multiply by $\frac{10^3}{\text{density}}$.

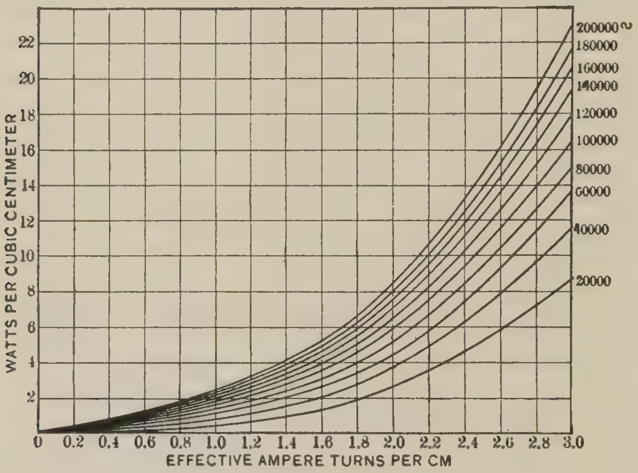

Fig. 71.—Core loss at constant frequencies and varying ampere-turns.

The characteristics of soft iron wires for frequencies up to 1,000,000 cycles have been obtained by Nusbaum.[8] The results are similar to those obtained by Alexanderson for the lower frequencies and show that, due to skin effect, the hysteresis and eddy losses per cycle for a given r.m.s. magnetizing force decrease with increasing frequency.

It is evident from the above described experimental results that the effective permeability and losses of a magnetic material may be calculated at least approximately for any frequency even up to high radio values from a knowledge of the electrical and low-frequency magnetic characteristics. Within limits the eddy losses may be decreased by making the material thinner, but usually with some increase in hysteresis loss. In general, even for very high frequencies, it does not pay to make the material much thinner than 1 mil due to the decreased space factor resulting from the necessary insulation between wires or laminations. In the case of high-silicon steel, moreover, it is difficult and expensive to roll to very thin gages. Latour[4] has developed a formula for calculating the most economical thickness of sheet taking into account the thickness of insulation.

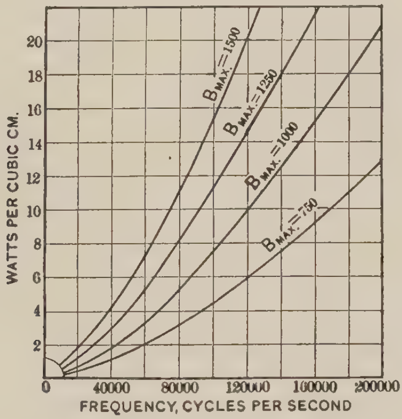

Fig. 72.—Core loss at constant apparent densities and varying frequency.

Some recent German work indicates that at very high radio frequencies there is a sort of magnetic resonance which produces a sudden and considerable change in the effective permeability of ferromagnetic materials.[9] The apparent permeability of iron wires is shown to vary in a rather erratic manner between frequencies of 1,000,000 and 6,000,000 cycles with a sharp maximum at about 3,000,000 cycles. This effect is largest for very small magnetizing forces. The shape of the permeability curve against frequency is similar to that of the index of refraction inside an absorption band. This effect may be of some importance in radio. It is certainly of very considerable theoretical interest because it indicates that the elementary magnets have a natural period of oscillation.

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CHAPTER VIII

EFFECTS OF DIRECTION OF GRAIN AND MECHANICAL STRESS ON MAGNETIC PROPERTIES

DIRECTION OF GRAIN

Due to the process of rolling, sheet material has imparted to it certain magnetic and other physical properties which are a function of the direction of rolling. As ordinarily carried out, the steel is rolled into long bars which are then cut into lengths approximately equal to the required width of the finished sheet. These bars are then rolled in the sheet mill in a direction at right angles to the direction of bar rolling. When the properties of a sheet parallel to the direction of grain are referred to, the direction parallel to the sheet rolling is meant. Unless the sheet has been pickled, a casual inspection will usually reveal this direction. An inspection under the microscope of an etched section of a sheet as it comes from the rolls will show that the grains are greatly elongated in the direction of rolling. After a suitable annealing, such as electrical sheet is ordinarily subjected to, these grains become much less elongated and larger in size. In fact, it is usually difficult to determine the direction of rolling by inspection under the microscope of a section of properly annealed sheet. Even though the grains no longer show marked unidirectional characteristics after annealing, nevertheless, there still persist decided differences in magnetic characteristics with different directions of grain.

Some years ago a considerable amount of data was obtained on the effect of direction of grain on the iron loss and permeability of 4 per cent commercial silicon sheet steel.[1] The first part of the investigation consisted in shearing Epstein samples (strips 50 by 3 centimeters), one half cut parallel to the direction of rolling and the other half at right angles, from a considerable number of heats* of commercial sheet. These samples were tested for total loss at 60 cycles and an induction of 10 kilogausses and for permeability at 6, 10, and 16 kilogausses. The material had the ordinary mill annealing before shearing. After testing, the samples were re-annealed, tested a second time, re-annealed once more, and finally tested for the third time. These samples were taken from 234 lots* of steel and therefore should give good average results. Later samples were taken from 89 more lots, and strips cut from each sheet parallel, perpendicular, and at 45 degrees to the direction of sheet rolling.

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* A *heat* consists of all of the steel tapped from an open-hearth furnace into a ladle.

TABLE VIII.—PER CENT WATT LOSS AS AFFECTED BY DIRECTION OF GRAIN

Based on the parallel-grain watt loss

Treatment	Perpendicular	Diagonal
As received	112.0	102.8
First anneal	114.2	105.6
Second anneal	114.9	107.0

The loss tests were made with the ordinary Epstein apparatus using a 5-kilogram sample, and the permeability tests were made on a Burrows permeameter of the compensated double-yoke type using approximately a 1-kilogram sample. Table VIII gives the per cent loss of the perpendicular and diagonal samples, with reference to the parallel samples. Table IX gives the per cent permeability of the perpendicular and diagonal samples with reference to the parallel-grain samples. Typical hysteresis loops taken on two samples cut from the same sheet, one with

TABLE IX.—PER CENT PERMEABILITY AS AFFECTED BY DIRECTION OF GRAIN

Based on the parallel-grain permeability

Treatment	B = 6000		B = 10,000		B = 16,000	
	Perpendicular	Diagonal	Perpendicular	Diagonal	Perpendicular	Diagonal
As received	71.0	87.8	70.4	94.6	76.2	113.2
First anneal	80.7	85.5	71.7	87.0	72.2	110.2
Second anneal	73.8	82.2	66.8	85.1	76.0	105.0

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* A *lot* of steel consists of that portion of a heat which is heat-treated together in one annealing charge.

the grain parallel and the other perpendicular, are shown in Fig. 73. The poorer permeability and the wider loop for the perpendicular sample are shown very clearly. Ten-kilogauss loops on parallel and diagonal samples show similar results but with smaller differences.

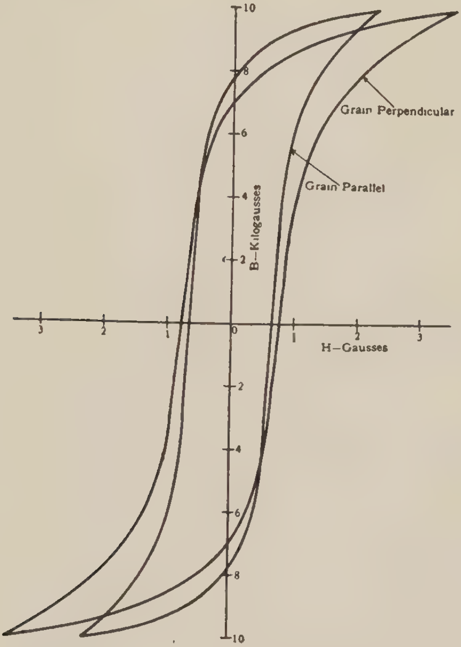

Fig. 73.—Effect of grain direction on shape of hysteresis loop.

Conclusions

1. On the average the losses at right angles to the grain are about 14 per cent higher than for the parallel direction.
2. The losses at an angle of 45 degrees with the direction of rolling are about 6 per cent higher than for the parallel-grain samples.
3. The permeability of the perpendicular-grain material is about 75 per cent of that of the parallel-grain steel for all inductions.
4. The permeability of the diagonal-grain material is about 85 per cent of that of the parallel-grain steel below 10 kilogausses, but at 16 kilogausses is about 110 per cent.
5. Wide variations from these mean values occur for individual samples both with respect to watt loss and permeability. In a few cases the diagonal- and even the perpendicular-grain material showed lower losses than the parallel-grain samples.

6. The difference between the samples cut in various directions is a function of the heat-treatment as well as the direction of rolling.
7. Whenever it can be avoided, sheet steel should not be used with the induction perpendicular to the direction of grain, since the magnetic properties under this condition are not good.

The high permeability at 16 kilogausses for the diagonal-grain samples is unexpected and no satisfactory explanation has been found. It has been pointed out by Ball and Ruder[2] that, since large grain size is accompanied by high permeability and low hysteresis loss, and that annealing does not altogether wipe out the elongation of the grains due to the rolling process, superior magnetic properties in the direction of rolling should be expected.

Medium- and low-silicon steels show effects similar to those given for the high-silicon sheet. Chief stress has been laid on the high-silicon steel, since losses and permeability are of prime importance in the case of this material. Since, apparently, it is inevitable that there should be this grain effect in spite of repeated annealing, it is well to know its magnitude in order that its effects may be minimized. In the case of small transformers, it is customary to use L plates with the grain at an angle of 45 degrees with the sides of the plates. This is done to aid in punching and to reduce the scrap to a minimum.

It will be seen from the above data that this increases the loss about 6 per cent over the parallel direction, but gives better results for exciting current if the inductions are high enough. For large transformers, when I plates are used the direction of grain should always be parallel to the long dimension of the plate. In the case of circular punchings for machines, there is, of course, no choice except that it should probably be advisable to have the grain in the same direction for all the punchings in order to prevent cross flux from one plate to another, due to differences in permeability, with consequent increase in eddy losses. In the case of segmental punchings, there is not much choice, since, if the grain is most favorable for the teeth, it will be unfavorable for the core. For high induction machines, it would probably be best to have the grain parallel to the teeth from permeability considerations.

Within commercial limits there is no difference in resistivity of electrical sheet with reference to the direction of grain. On this basis no difference in eddy-current losses would be expected. It is possible, however, that, due to the influence of grain boundaries, concerning which little is known, there may be a relation between direction of grain and eddy losses. Conclusive data in regard to this effect is wanting.

EFFECTS OF MECHANICAL STRESS (MAGNETOSTRICTION)

The relation between mechanical stress and magnetic properties is a most interesting subject and one which has engaged the attention of investigators for the last 75 years. The curious phenomena in this connection provide many a stumbling block, as well as much aid, to those who wish to formulate a theory of magnetism. Ewing's chapter on this subject* is so extensive that it is beyond the scope of this article even to summarize it adequately, to say nothing of referring even casually to the results of many subsequent investigations. Since magnetostriction, with a few exceptions, is at present chiefly of theoretical interest, the student is referred to Ewing for a general survey of the subject, this chapter being confined to a brief summary together with a presentation of some recent data of some commercial importance dealing with sheet material.

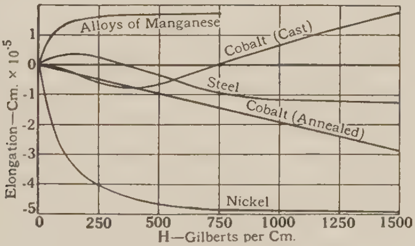

Fig. 74.—Changes in length of various materials due to magnetic fields.

Magnetostriction deals with the reciprocal relations between changes in dimensions caused by magnetism and changes in magnetic properties caused by stress. These properties are quite different, not only in magnitude but in quality for different ferromagnetic materials. Suppose a longitudinal magnetizing force is applied to a bar of steel, the bar will at first expand. If the magnetizing force is increased sufficiently, the bar will return to its original length and then, as the value of H is further increased, will start to contract. Just the opposite is true for cobalt. Some typical curves are given by Fig. 74.[3] This is known as the *Joule magnetostrictive effect.* Now, if a bar of iron is subjected to a small magnetizing force, and a load is applied in the same direction, the induction will increase. Again, if a large magnetizing force is applied, the induction will decrease with increasing load. Figure 75 illustrates these effects. The point at which the initial and the loaded curves cross is called the Villari reversal point and varies with the load as indicated. Figure 76 shows similar curves for nickel except that the induction decreases with load for all values of magnetizing force. Cobalt under compression shows the same kind of changes as iron under tension including the Villari reversal effect.

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* "Magnetic Induction in Iron and Other Metals," Chap. IX, p. 197, 3d ed.

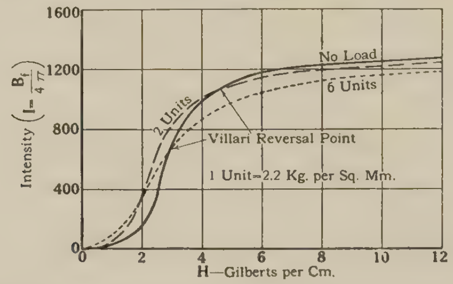

FIG. 75.—Magnetization of annealed iron under various amounts of longitudinal pull.

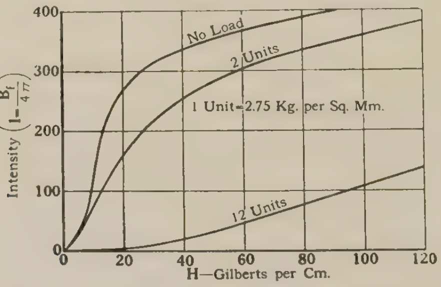

FIG. 76.—Magnetization of annealed nickel wire under various amounts of longitudinal pull.

In general the following relations hold:

1. Iron and cobalt show reversals in magnetic effects when stress is applied depending on the magnitude of the magnetizing force, while nickel and manganese alloys do not.

2. When a ferromagnetic material lengthens in a magnetic field the same field will produce an increase of magnetic induction when the sample

is put under tension. When it contracts in a magnetic field, the reverse will be true.

3. When there is an increase of magnetic induction with tension, there will be a decrease with compression. When there is a decrease of induction with tension, there will be an increase with compression.

4. If a load is applied to a magnetized specimen with a resulting change in induction, the induction will not, in general, return to its original value on removal of the load even though the stress is far below the elastic limit. This hysteresis effect is different for the second cycle than for the first, but a cyclic condition is soon reached.

5. The material, if it has not been stressed beyond the elastic limit, may be returned to its original state by suitable demagnetization.

6. Mechanical vibration greatly reduces these hysteresis effects.

Another series of phenomena are called the Wiedemann effects. If a rod is subjected to a longitudinal field by means of a solenoid or similar means and to a circular field by passing current through it from end to end, it will be shortened or lengthened depending on the material and at the same time be given a twist. Conversely, if a bar or wire is placed in a longitudinal field and twisted or is twisted and stressed longitudinally, many curious changes in magnetic induction occur. These effects cannot be gone into here, but are dealt with quite fully by Ewing and others.

It is possible that at some later date these magnetostrictive phenomena may become of considerable commercial importance, but at present the concern is with only a few of the simpler effects as noted below.

Electrical Sheet.—Electrical sheet is subjected to a variety of strains both below and above the elastic limit. In general, these strains are harmful to the magnetic properties, though there are a few exceptions as will be noted later. If, due to incorrect annealing, a sheet is wavy or bent, when it is assembled into the completed apparatus it will be straightened out and strains introduced. Since this is a bending effect, the strains will be both tension and compression. In the process of punching, the edges of the sheets are strained beyond the elastic limit, producing permanent strains which penetrate an appreciable distance into the sheet. This is quite important with reference to the hysteresis loss in the teeth of small motors, as will be shown later. These illustrations are given simply to show the desirability of considering the effects of mechanical strain with reference to the magnetic properties of the cores of electrical apparatus. Sometimes, these effects cannot be safely neglected.

Effects of Punching.—Under this heading will be considered those processes which involve cutting the sheet to size; namely, punching and shearing. When a sufficiently large number of pieces of the same size and shape are required to warrant the construction of dies, punching is resorted to; but, when only a comparatively small number of pieces is needed, shearing or slitting is used. Punching is now common for quite large plates.

That punching increases the hysteresis loss and decreases the permeability has been known for a long time, but very little quantitative data has been available. Recently, however, some more extensive test data has been obtained, as reported by G. H. Cole.[4]

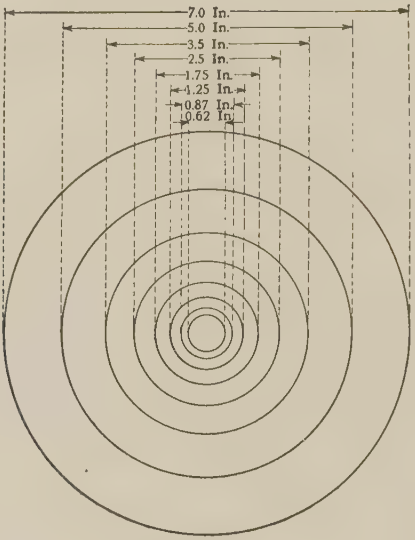

FIG. 77.

A series of rings were punched from sheet material of various kinds, the smaller rings being punched from the centers of the larger rings as shown by Fig. 77. Table X shows the kinds of material investigated and the thickness of the sheets. It will be noted that the ratio of radial width to diameter is approximately 6 for all of the rings.

These samples were tested ballistically by obtaining hysteresis loops for a maximum induction of 10 kilogausses for all of the rings, and for 16 kilogausses for some of the rings. The samples

TABLE X.—STEEL USED FOR PUNCHING INVESTIGATION

Material	Thickness of sheet*
4 per cent silicon.....	0.014 (0.36)
2.5 per cent silicon.....	0.014(0.36), 0.017(0.43), 0.025(0.64), 0.031(0.79), 0.0625(1.59), 0.078(2.0),
1 per cent silicon.....	0.017 (0.43)

* Dimensions are given in inches; dimensions in parenthesis are in millimeters.

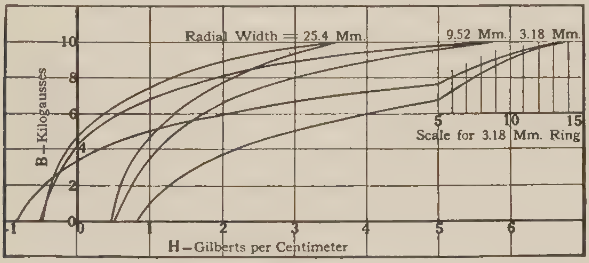

FIG. 78.

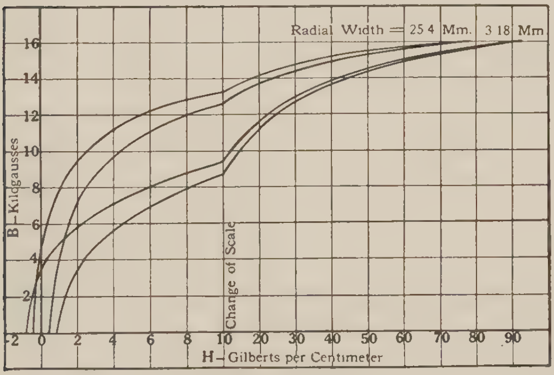

FIG. 79.

were then annealed at 450°C., re-tested, then re-annealed at 700°C., and again tested. Figure 78 shows a typical set of 10-kilogauss hysteresis loops for a large, a medium-sized and a small ring of 4 per cent silicon steel. Figure 79 gives 16-kilogauss loops for the same large and small rings. The very large change in permeability at moderate inductions for the small rings and the small change in permeability at 16 kilogausses should be especially noted.

Table XI shows the hysteresis and permeability results for a maximum induction of 10 kilogausses for all the rings tested, with no heat-treatment after punching. There are included a few rings of 4-mil 4 per cent silicon steel to show the effect on very thin

TABLE XI.—HYSTERESIS LOSS AND PERMEABILITY AT 10 KILOGAUSSES

No treatment subsequent to the punching operation

Per cent silicon content (nominal)	Thickness of sheet steel		Radial width of specimens		Hysteresis loss	Permeability
	Millimeters	Inches	Millimeters	Inches	Ergs per cycle per cubic centimeter	
One	0.44	0.017	3.18	0.125	5280	940
			4.75	0.187	4790	1050
			6.35	0.250	3740	1880
			9.52	0.375	4190	1270
			12.7	0.500	3645	1740
			19.0	0.750	3480	2030
			25.4	1.000	3110	2890
Two	0.36	0.014	3.18	0.125	3910	704
(Lot A)	....	.....	4.75	0.187	2860	1250
			6.35	0.250	2510	1540
			9.52	0.375	2755	1410
			12.7	0.500	2620	2090
			19.0	0.750	2430	2580
			25.4	1.000	2435	2550
Two	2.00	0.078	3.18	0.125	5540	425
(Lot B)	....	.....	9.52	0.375	3860	793
			25.4	1.000	2405	1970
Two	1.60	0.062	3.18	0.125	4950	502
(Lot B)	....	.....	9.52	0.375	3535	847
			25.4	1.000	2260	2380
Two	0.80	0.031	3.18	0.125	4370	565
(Lot B)	....	.....	9.52	0.375	3255	877
			25.4	1.000	2005	3030
Two	0.63	0.025	3.18	0.125	4780	588
(Lot B)	....	.....	9.52	0.375	3340	926
			25.4	1.000	2060	3230
Two	0.44	0.017	3.18	0.125	4230	670
(Lot B)	....	.....	9.52	0.375	2880	1134
			25.4	1.000	1992	3280
Four	0.01	0.004	3.18	0.125	3851	1350
			9.52	0.375	3030	2910
			25.4	1.000	2960	3100
Four	0.36	0.014	3.18	0.125	2590	727
			4.75	0.187	2020	1160
			6.35	0.250	1830	1260
			9.52	0.375	1653	1740
			12.7	0.500	1878	2350
			19.0	0.750	1355	2610
			25.4	1.000	1395	2780

gage material. Table XII shows similar results for a maximum induction of 16 kilogausses for a few of the rings. Table XIII shows the effect of annealing at 450°C. and 700°C. on the hysteresis losses, and Table XIV the effect on the permeability. It should be noted particularly that a temperature of 450°C. is

TABLE XII.—HYSTERESIS LOSS AND PERMEABILITY AT 16 KILOGAUSSES

No treatment subsequent to the punching operation

Per cent silicon content (nominal)	Thickness of sheet steel		Radial width of specimens		Hysteresis loss	Permeability
	Millimeters	Inches	Millimeters	Inches	Ergs per cycle per cubic centimeters	
One	0.44	0.017	3.18	0.125	11,415	305
			25.4	1.000	9,540	435
Two	0.36	0.014	3.18	0.125	8,695	186
(Lot A)	....	.....	25.4	1.000	7,690	269
Two	2.0	0.078	3.18	0.125	9,540	160
(Lot B)	....	.....	25.4	1.000	6,100	308
Four	0.36	0.014	3.18	0.125	6,215	172
			25.4	1.000	5,295	205

TABLE XIII.—EFFECT OF ANNEALING IN REDUCING THE HYSTERESIS LOSS

Of rings having different punching stresses

Per cent silicon content (nominal)	Radial width of ring, millimeters	Thickness of sheet, millimeters	Hysteresis loss in ergs per cycle per cu. cm.					
			10 kilogausses			16 kilogausses		
			Unannealed	Annealing temperature		Unannealed	Annealing temperature	
				450°C.	700°C.		450°C.	700°C.
One	3.18	0.44	5,280	4,412	2,527	11,415	8,879	7,600
	25.1	0.44	3,110	2,846	2,331	9,540	7,244	6,932
Two	3.18	0.36	3,910	3,667	1,788	8,695	7,307	6,583
	25.1	0.36	2,435	2,292	1,801	7,690	7,803	6,130
Two	3.18	2.00	5,540	4,195	1,473	9,540	7,288	4,249
	25.1	2.00	2,405	2,527	1,760	6,100	5,804	4,418
Four	3.18	0.36	2,590	2,492	1,174	6,212	4,595	3,314
	25.1	0.36	1,395	1,378	1,107	5,295	4,684	4,188

TABLE XIV.—EFFECT OF ANNEALING ON THE PERMEABILITY
Of rings which have different punching stresses

Per cent silicon content (nominal)	Radial width of ring, millimeters	Thickness of sheet, millimeters	Permeability					
			10 kilogausses			16 kilogausses		
			Unannealed	Annealing temperature		Unannealed	Annealing temperature	
				450°C.	700°C.		450°C.	700°C.
One	3.18	0.44	940	1,317	3,920	305	341	196
	25.1	0.44	2,890	3,380	4,950	435	568	341
Two	3.18	0.36	704	1,020	5,150	186	202	149
	25.1	0.36	2,550	2,830	4,540	269	258	213
Two	3.18	2.00	425	736	7,880	160	229	256
	25.1	2.00	1,970	1,740	4,600	308	390	320
Four	3.18	0.36	727	1,000	5,560	172	200	174
	25.1	0.36	2,780	3,070	6,320	205	215	213

sufficient to wipe out the punching strains only partially, but that 750°C. not only eliminates them entirely, but gives a material which is superior to the unpunched steel.

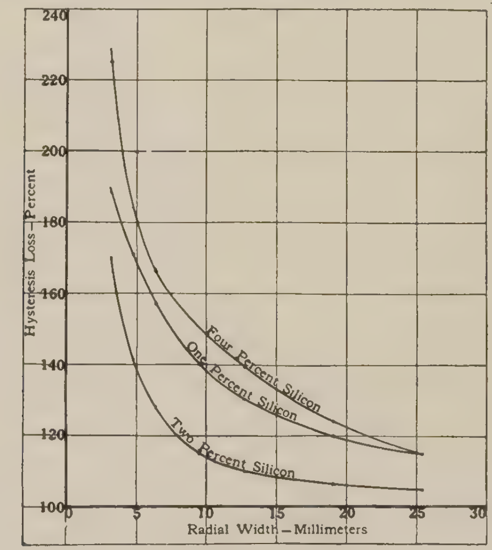

FIG. 80.

Figure 80 shows the per cent increase of hysteresis loss due to punching as a function of radial width for the three grades of steel. Figure 81 shows similar curves for various thicknesses of medium-silicon steel. These curves do not check those of Fig. 80 for medium-silicon steel, since the material is somewhat different and the punchings were made at a different time. Figure 82 shows the relation between permeability and radial width. All of these curves are for the 10-kilogauss loops.

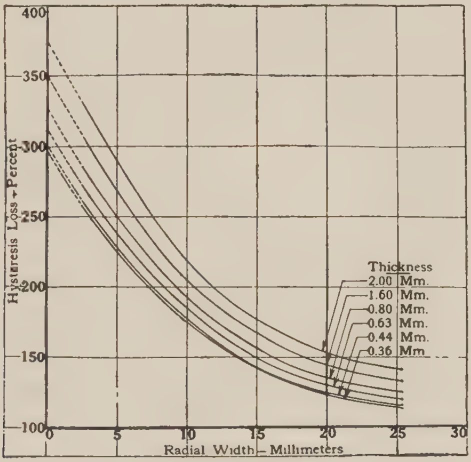

FIG. 81.

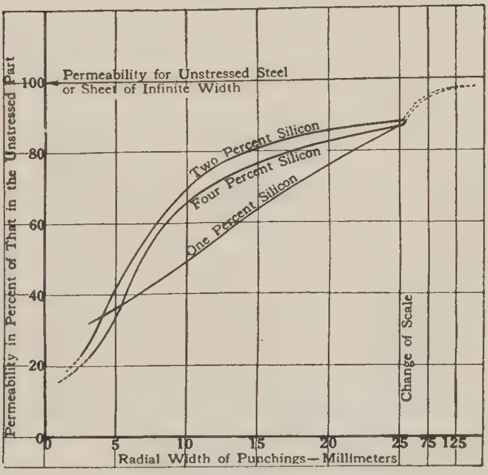

FIG. 82.

The results of this punching investigation may be summarized as follows:

1. The strains produced by the punching operation increase the specific hysteresis loss very greatly in a narrow section next to the punched edge. The average core loss in sections as narrow as the teeth of small induction motors may be increased 100 per cent or more by punching strains.

2. For fairly sharp dies, the increased hysteresis loss in per cent of that of the unstressed steel may be calculated approximately by dividing 35 by the width of the steel laminations in centimeters, or 14 by the width in inches for moderate inductions.

3. Fortunately, the per cent increase of hysteresis loss at high flux densities (such as frequently exist in the narrow section of the teeth of motors) is much smaller than at the more moderate inductions, which generally exist in the wider sections of the magnetic core. The effect of punching, however, is by no means negligible at 16 kilogausses, as may be seen from the fact that a punching with a radial width of 3.18 millimeters (0.125 inch) had a hysteresis loss which averaged 25 per cent higher than that of specimens having a radial width of 25.4 millimeters (1.0 inch).

4. Increased hysteresis losses produced by punching strains are approximately a linear function of the thickness for those studied, but do not approach zero for thin materials.

5. In the range covered, the influence of gage on punching strains was much less than that of the width of the specimens.

6. No relation is apparent between the silicon content of the steel and the increased energy loss produced by punching.

7. Annealing at 450°C. partially eliminates the punching strains. When a maximum temperature of 700°C. was used, the effect of the punching operation upon the hysteresis loss was not only wiped out, but, generally, an improvement over the unpunched condition was effected.

8. The permeability at 10 kilogausses was greatly affected by the punching operation. In the widest punching tested, the permeability was reduced by more than 10 per cent, while, for the naarrowest specimens, it was lowered to 20 or 30 per cent of its normal value. It is probable, judging from further tests (not reported by Cole), that strains would have an even larger effect on the permeability at the flux density corresponding to maximum permeability (from 6 to 8 kilogausses).

9. In the narrower punchings corresponding to the teeth of motors of small or medium size, the permeability at high flux density, such as 16 kilogausses, was reduced by 30 per cent or more.

10. Annealing even at such a low temperature as 450°C. produced a large improvement in the permeability at 10 kilogausses, but still left wide differences between the narrow and wide specimens. At 16 kilogausses the permeability was generally poorer after annealing at 700°C. than after the 450°C. treatment. This is probably due to oxidation, since proper annealing will improve the permeability even at this moderately high flux density. At 10 kilogausses, however, the higher annealing

temperature produced a very large improvement in permeability of all specimens. In the narrowest samples this permeability was raised to a value at least 4 times as high as in the condition in which it was left by the punching operations, while in one specimen of heavy gage it was raised to 18 times its former value.

The effect of shearing is similar to that of punching. It is not so important, however, since sheared pieces are usually fairly wide and the shearing effect in per cent of the total loss is therefore small. By using very sharp shears, it is possible to make the effect of shearing quite small. In general, it may be assumed that shearing will produce approximately the same quantitative changes in hysteresis loss and permeability as punching.

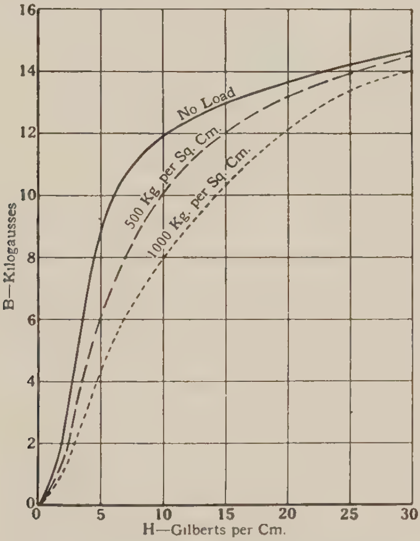

FIG. 83.—Silicon steel under compression.

Effect of Tension and Compression.—A number of investigations of the effect of tension on the magnetic properties of steel have been made at various times. Smith and Sherman have reported some typical results.[5] They tested rail steel, wrought iron, mild steel, and silicon steel. The tests were evidently made with considerable accuracy, using a modification of the Burrows permeameter. The results for silicon steel are given in Figs. 83 and 84. It will be noted that the effect of compression is much greater than that of tension, and for low inductions the effects are in opposite directions; namely, compression reduces the permeability but tension increases it. At high inductions and loads it will be noted that tension also decreases the permeability. This effect is known as the Villari effect, as noted above. It is possible that, if the inductions were carried high enough, this reversal would also occur for compression. The other materials showed similar effects, but of different amounts. The wrought iron showed even larger magnetic sensitivity to strains than the silicon steel, while the rail steel and mild steel were much less affected.

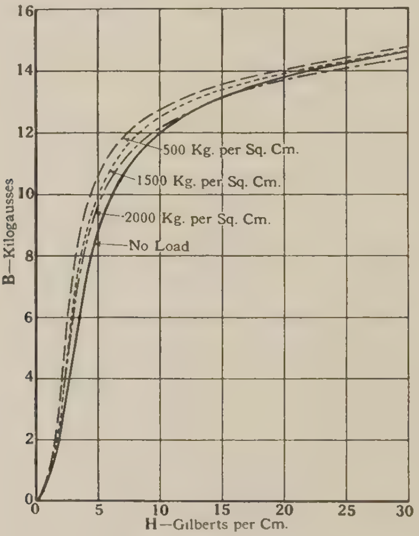

FIG. 84.—Silicon steel under tension.

Ewing and others have reported similar test results obtained on wire samples. These results of Smith and Sherman are particularly interesting since they were made on more homogeneous material of much larger cross-section. Their conclusions are as follows:

> It will be seen in comparing the tension and compression curves that, when a bar is placed under compression and a low magnetizing force is applied with a successively decreasing load, the permeability gradually increases with a steady decrease in this rate of increase as zero load is approached. If new tension is applied, the permeability still increases at a diminishing rate until a certain value of load is reached at which the increase ceases and reverses, the permeability becoming smaller as more load is applied. The change in rate seems nearly constant and is in the same direction throughout.

A more recent investigation made by Fraichet[6] yields the following conclusions:

1. Only elastic deformations cause the variations of intensity of magnetization.
2. Permanent deformations, producing a contraction of the cross-section of the bar, only diminish the magnetic flux according to a straight-line law.

He further states that the variations connected with elastic deformations are large; those connected with permanent deformations are small. Fraichet believes that permanent deformations cause slip of molecules without change of distance between them; on the contrary, elastic deformations change distances between the molecules, which also cause variations of magnetization. He further states that the true elastic limit of a material can be accurately determined by magnetic tests.

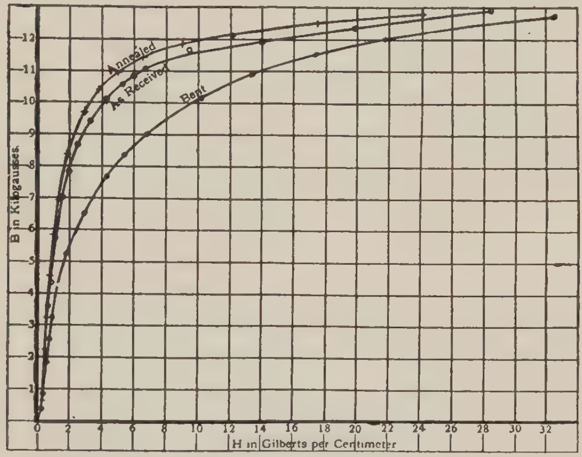

FIG. 85.—Effect of bending and annealing on magnetization. Of 0.0125-inch laminated, 4 per cent silicon-steel rings.

Effect of Bending.—As mentioned above, the effect of bending is the resultant of the effects produced by tension and compression. Since compression produces much greater magnetic effects than tension, the effects of bending are similar to those produced by the former. The laminated cores of practically all electrical apparatus are subjected to some extent, at least, to bending strains. It is important, therefore, to know the magnitude of these bending effects in order to know to what extent it is necessary to take pains to reduce them.

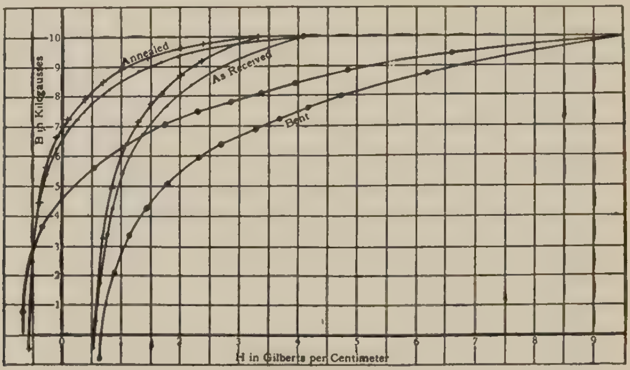

Fig. 86.—Effect of bending and annealing on hysteresis. Same sample as in Fig. 85.

Figure 85 shows the magnetization curves and Fig. 86 the hysteresis loops on a ring sample of laminated material taken first in the unstrained condition, then, under strain below the elastic limit, and, finally, after annealing under the strained condition. The strains were produced by bending the ring sample with the test windings still in position as indicated by Fig. 87. It will be noted that the permeability is greatly decreased by bending at moderate inductions, but is not affected at high inductions. The hysteresis loss is increased about 15 per cent by this particular stress. If the stress is removed, the material returns to its original condition. When the stress is removed by annealing, the material is better than in its original condition due to the fact that not only are the strains removed, but an improvement has been effected by annealing. For stresses below the elastic limit, the hysteresis loss increases approximately in inverse proportion to the radius of curvature. For a given radius of curvature, the effect of bending, of course, is greater the thicker the material, because the stresses are greater.

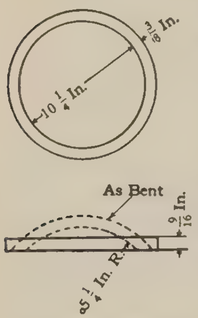

Fig. 87.—Sample used to show effect of bending.

Some materials are much more affected by mechanical strains than others. For instance, permalloy, having a composition of 78 per cent nickel and 22 per cent iron, is extremely susceptible to strains. When using this or similar material, it is often desirable to anneal the laminations after assembly into the completed core. In general, it may be said that the better the magnetic quality of the material (the higher the permeability and the lower the hysteresis loss) the greater will be these mechanical effects.

When material is stressed beyond the elastic limit, there results a permanent decrease in magnetic quality which can be wiped out only by suitable annealing. If it is true that only strains below the elastic limit produce marked magnetic changes, then the large magnetic changes due to permanent deformation such as produced by severe bending must be due to strains below the elastic limit in certain portions of the material.

Hydrostatic Pressure.—When subjected to hydrostatic pressure, magnetic materials undergo a change in magnetic properties, but these changes are much less than those which result from ordinary compression or tension, due perhaps to the fact that hydrostatic pressure distorts the space lattice less than is the case for the more common types of strain. Frisbie[7] reports the following conclusions from a series of experiments along this line:

> 1. The application of hydrostatic pressure to soft iron anchor rings changes the coefficient of magnetic permeability of the iron, besides altering the amount of residual magnetism when the pressure is applied or removed. The amount of change varies for different pieces of iron.
> 2. With unannealed iron the sign of the change depends upon the strength of the magnetic field, the effect in small fields being a decrease and in strong fields an increase; the change of sign occurs for 4.5 or 5 c.g.s. units. The magnitude of the alterations is a function of both field and pressure.
> 3. With annealed iron, an increase is found for pressure with all values of field between 0.54 and 9.67 absolute units.

These effects are of the order of 2 or 3 per cent for pressures up to 16,000 pounds per square inch.

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CHAPTER IX

EFFECT OF HEAT-TREATMENT

Annealing is a very important factor in the manufacture of electrical sheet. After coming from the rolls the material has high hysteresis loss and low permeability. By suitable annealing the hysteresis loss may be reduced to one-half or less of its unannealed value and the maximum permeability increased many hundred per cent. At very high inductions heat-treatment does not affect the permeability of electrical sheet to any large extent, unless it is accompanied by oxidation. Permanent-magnet steels of the more common types are of no value at all as such until they have been heat-treated, since the coercive force for chromium and tungsten steels is often one-third or less of its maximum value as the material comes from the rolls.

ELECTRICAL SHEET

After the rolling operation is completed, electrical sheet is given what is called a mill annealing. This consists in heating the sheets to from 800 to 1000°C. or sometimes even higher, and then cooling them slowly. In many cases the annealing cycle occupies several days. In order that the sheets shall not be injured by oxidation, it is essential that the material be protected from the air. This is done usually either by stacking the sheets on a car and placing a cover over them with a seal of sand or other material at the bottom to prevent air circulation, or the steel is packed in boxes. Since the charge is often large, consisting, sometimes, of 30,000 pounds or more, a perfect seal is not required, as the small amount of oxygen which does penetrate is not sufficient to do any appreciable harm. Various types of furnaces are used, such as the car type, pit type, continuous, etc., and various kinds of heating are successfully used. Any of these types of furnaces, if properly designed, is capable of giving good results, the only essentials being slow cooling and no appreciable oxidation. In some cases it may be desirable to use an atmosphere of nitrogen or hydrogen, or even a vacuum. A hydrogen atmosphere has the advantage that it will often reduce some of the oxidation which may have taken place due to the previous mill operations. High-silicon steel oxidizes much less readily than low-silicon steel. For this reason, more pains must be taken to prevent oxidation with the latter. These precautions sometimes consist merely in using a lower firing temperature, since oxidation is a function of temperature as well as the oxygen content of the atmosphere.

The objection to excessive oxidation is twofold. For moderate oxidation, the hysteresis loss and permeability at medium inductions are not affected to any considerable extent, but the high-induction permeability may be quite appreciably reduced. This is a decided disadvantage for rotating machines and transformers which operate at high inductions. Under the worst oxidizing conditions which are met in practice, the permeability at 16 kilogausses, for instance, may be decreased from 20 to 30 per cent, and the hysteresis loss may be increased to a slight extent over that which would occur under suitable annealing conditions. The second objection to large oxidation is that, for low-silicon sheets, at least, the material may stick together, so that it is difficult to separate the individual laminations. A high-induction permeability test is sometimes made as a commercial test to determine whether or not the furnace oxidizing conditions are excessive. This subject of oxidation has been emphasized here because it is often one of the chief sources of difficulty in furnace design and operation.

It should be mentioned that, as shown by Yensen, a certain amount of oxidation is desirable, since it reduces the carbon content of the steel. The carbon diffuses toward the surface, is there oxidized, and passes off in the form of a gas. The amount of oxidation for the best results is rather critical, however, and great care has to be taken not to exceed it. Sometimes, sufficient oxidation is produced by the oxides already on the surface of the sheets.

For transformer punchings and for many types of rotating machines, it is common in this country to re-anneal the material after punching. Where papered sheets are used, this procedure is, of course, out of the question. This second annealing relieves the punching strains which, as has been pointed out, are often large when the punchings are narrow, and further reduces the hysteresis losses and increases the permeability beyond what would result merely from removing the strains. For a strip $1\frac{3}{16}$ inches (3 centimeters) wide, re-annealing may reduce the 60-cycle losses from 10 to 15 per cent or even more, and may increase the maximum permeability 50 per cent or more. The permeability at 16 kilogausses, in general, will be little affected. In annealing punchings for rotating machines, there is danger of the punchings being warped. This is undesirable, of course, as the punchings will no longer register properly.

It is possible to omit the mill annealing and anneal only after punching. The result of this practice, if the annealing is properly done, will be almost the same as is obtained with the double annealing. It is not a very safe procedure, however, since the finished punchings usually cannot be readily tested, and, if the annealing is not satisfactory, very inferior apparatus may result. The cost of the double annealing, in general, is slight and is quite worth while, at least for transformer punchings.

In most cases slow cooling is necessary in order to obtain the best results where low hysteresis loss and high permeability are required. There is one notable exception to this; namely, the nickel-steel alloys having nickel contents of over 50 per cent. For most of these alloys, the best results are obtained if the material is cooled quite rapidly from the magnetic recalescence point down to about 300°C. This cooling should be as rapid as possible without being sufficiently rapid to introduce internal strains into the material. It is probably for this reason that the remarkable properties of alloys of the permalloy type remained so long undiscovered; namely, that everyone familiar with the magnetic properties of materials believed that slow cooling, after the annealing, was essential to the attainment of high permeability and low losses.

If the grain size is not appreciably altered, annealing probably does not affect the eddy losses to any considerable extent, since it changes the resistivity very little. When the grain size is increased by annealing, the eddy losses may be very appreciably increased as pointed out previously.

The heat cycles, through which the material goes in the process of rolling, also affect the magnetic properties and persist even through the final annealing process; but a discussion of these effects is beyond the scope of this book. The heat treatments also affect the thickness and quality of the scale which, as has been previously pointed out, produces a considerable effect on the losses at high inductions. The change in the quality of the scale is dependent on the temperature and the extent to which the atmosphere is oxidizing.

AGING

In the earlier days of the electrical industry, there was a temperature effect which caused considerable concern both to the manufacturer and user of electrical apparatus, namely, aging. When annealed soft iron or steel, such as bessemer steel, is kept at a temperature of the order of 100°C. its hysteresis loss gradually increases with time. This effect may continue for weeks or even months. The increase is sometimes 100 per cent or more. Due to the fact that electrical apparatus operates near this temperature when fully loaded, aging was a very real source of difficulty, especially in the case of transformers. Since the advent of silicon steel, however, aging has ceased to be a matter of any considerable importance. Four per cent commercial silicon steel has such slight aging that it is entirely negligible. Even with the low-silicon electrical sheet of modern manufacture, the average aging is only a few per cent and causes no concern.

Aging has been shown to be entirely a temperature effect and takes place whether the material is magnetized or not. According to the American Society for Testing Materials specifications, it is the percentage increase in total iron loss for 60 cycles and a maximum induction of 10 kilogausses after subjecting the material to a temperature of 100°C. for 600 hours. The aging process is not always completed in this length of time, as it sometimes goes on for many weeks, but the aging is much more rapid at first as a rule, so that at the end of 600 hours the greater part of it has usually taken place.

Aging is usually most rapid at about 130°C. A material which shows considerable aging at this temperature may show little or no aging at a temperature of 300° or more. The true cause of aging is at present unknown. It is probably the result of some slow structural changes, such as, perhaps, the slow reabsorption of carbon which has been thrown out of solution by previous heat-treatment.

While aging is of no particular importance with reference to commercial electrical sheet, the analagous effect of maturing, in the case of permanent-magnet steels, which has already been discussed is of very considerable importance, and is given much attention by the manufacturers of electrical measuring instruments. A 2 or 3 per cent increase in the losses of a transformer or motor does not matter particularly, but a similar change in the calibration of a watt-hour meter which is measuring large blocks of power may involve a considerable sum of money.

In the development of new magnetic alloys, this matter of aging must be looked into. In the earlier stages of the development of Yensen's vacuum iron, for instance, the aging was carefully checked and found to be negligible for high-quality material. Again, soon after the discovery of permalloy, the aging effect was determined and found to be negligible. In this connection it may be mentioned that the mere presence of, say, 4 per cent of silicon in an iron alloy does not insure the absence of aging, although commercial electrical sheet of this composition is practically nonaging. If sufficient carbon and certain other impurities are present, the aging may be considerable. When, however, the alloys are of such purity that the hysteresis loss is low, it is safe to assume that the aging of high-silicon steel will be negligible.

CARBON AND ALLOY STEELS

Those materials not included under the heading of electrical sheet will be considered here. For solid materials, when low hysteresis or coercive force and high permeability are required, an ordinary anneal similar to that used for electrical sheet is usually sufficient. The rate of cooling should be slow, and the maximum temperature varies over a considerable range, depending on the material. This annealing serves the double purpose of relieving mechanical strains due to the fabricating process and to rapid cooling, and also allows carbon, if it is present in combination, as would usually be the case with rapid cooling, to precipitate in a form which is least harmful to the magnetic properties.

Quenching and drawing are of interest from a magnetic standpoint chiefly with reference to permanent-magnet steels* and in connection with magnetic analysis.† In this chapter, then, will be given only a very general and superficial discussion of the subject.

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* The heat-treatment for these materials was discussed in Chap. V.

† See Chap. XXV.

The effect of heat-treatment on iron alloys, in general, is largely a function of the carbon content and the way in which the previous thermal history has caused the carbon to combine with the other elements. In order to consider this subject intelligently, it is essential to deal with it with reference to the iron-carbon diagram as was done in connection with the discussion of the heat-treatment of permanent-magnet steels. This diagram is profoundly modified by certain alloying elements and their effect must be known at least approximately. Figure 88 shows the iron-carbon diagram as given by Howe,[1] with a few slight modifications.

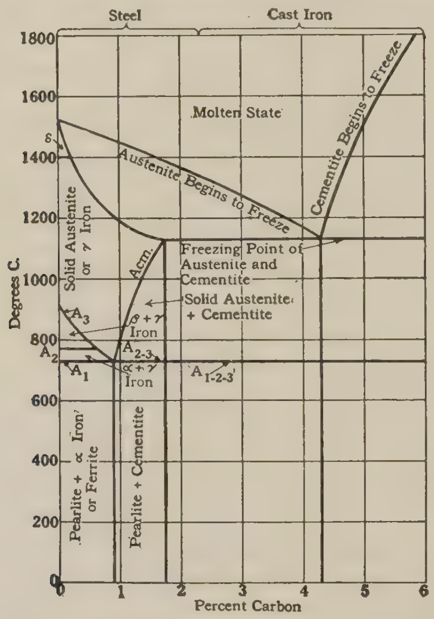
Steel
Cast Iron
1800
1600
1400
1200
1000
800
600
400
200
0
δ
A2
Degrees C.
Molten State
Austenite Begins to Freeze
Cementite Begins to Freeze
Solid Austenite or γ Iron
Acm.
Freezing Point of Austenite and Cementite
Solid Austenite + Cementite
A3
β + γ Iron
A2-3
α + γ Iron
A1
A1-2-3
Pearlite + α Iron or Ferrite
Pearlite + Cementite
0
1
2
3
4
5
6
Percent Carbon

FIG. 88.—Iron-carbon equilibrium diagram.

Critical Points.—First, the condition for pure iron will be considered. At a temperature above 1400°C. iron is in the so-called δ state. It is feebly magnetic and has the body-centered structure of iron at normal temperature. As the iron cools through 1400°C., the Ar_4 transformation takes place, this transformation consisting in the change of atomic structure from the body-centered form to the face-centered form, like that of nickel.[2] The material is now in the γ state and has lost practically all of its magnetic properties. At about 920°, the atomic structure again changes to the body-centered form, β iron being formed, but does not yet regain its magnetic properties. This is the Ar_3 transformation. At 768°, however, the iron suddenly begins to become magnetic, but without any known change in atomic structure. This is the Ar_2 transformation and α iron is formed. There is no further transformation for pure iron clear down to the lowest temperature obtainable.

Now, if the temperature is increased, the reverse changes take place, but the transformations, in general, will occur at somewhat higher temperatures. This is especially true for the A_1 transformation to be described later. By making the rate of heating and cooling sufficiently slow, these transformation temperatures can be made nearly to coincide. The transformation points for heating are called the Ac points, and for cooling, the Ar points.

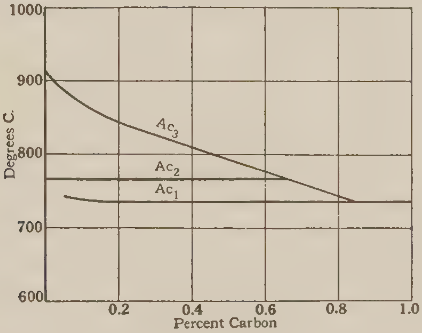

FIG. 89.—Iron-carbon equilibrium diagram.

These transformation temperatures are usually determined by placing a thermocouple in a small specimen and then obtaining the time-e.m.f. curve as the applied temperature is changed at a uniform rate. A pause in the rate of heating or cooling of the specimen will indicate the transformation point, as these changes are accompanied by the absorption or giving out of heat. The A_2 point often can be more easily determined magnetically, and this is sometimes done in connection with commercial heat-treatment.

When carbon is added to iron, these transformations still exist, but some of them change markedly in temperature, as indicated by Figs. 88 and 89. The latter diagram is due to Pilling and shows, to a larger scale than Howe's diagram, the more limited range of temperature and carbon content which is of most interest. With increase of carbon up to 0.85 per cent the A_3

transformation steadily decreases in temperature. The A_2 temperature is practically unchanged until a carbon content of 0.65 is reached, where the A_3 and A_2 transformations coincide. As soon as slight amount of carbon is present, a new transformation appears; namely, the A_1 transformation, and this remains at practically the same temperature for all carbon contents

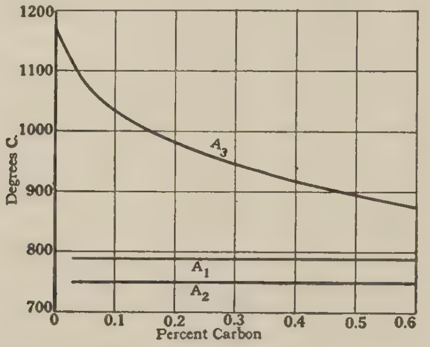

FIG. 90.—Iron-carbon equilibrium diagram for 2 per cent silicon.

This transformation marks the formation of pearlite, which is a combination of cementite (FeC_3) and ferrite (pure iron). These two constituents often occur in alternate layers, and in this condition give the typical pearlitic structure which is so familiar to the metallographist. It will be noted that, at 0.85 carbon, the three transformations A_1, A_2, A_3 coincide. This is true also for all

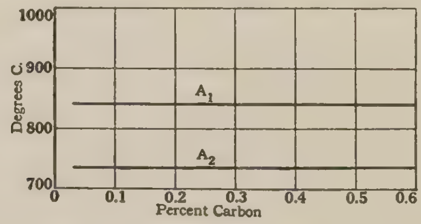

FIG. 91.—Iron-carbon equilibrium diagram for 4 per cent silicon.

higher carbon percentages. Referring to Fig. 88, for carbon percentages higher than 0.85, a transformation *Acm* is shown which marks the formation of cementite. For a temperature below the A_1 point, if the carbon percentage is below 0.85, there will be found, at least for slow cooling, pearlite plus a certain amount of pure iron or ferrite, the percentage of ferrite being greater the less the carbon content. At 0.85 carbon, the structure is entirely pearlitic. Above 0.85 carbon, pearlite exists with an excess of cementite. The exact temperature at which these transformations occur varies with the rate of heating and cooling, the *Ac* or heating points being less subject to time lag and, of course, being higher than the cooling or *Ar* points. A complete discussion of this diagram is beyond the scope of this book, and different metallographists differ in their interpretation of the diagram. Some metallographists do not admit the existence of β iron, for instance, but consider that the change from γ iron is direct to α iron.

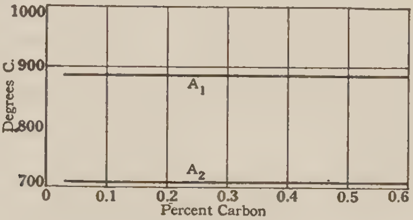

FIG. 92.—Iron-carbon equilibrium diagram for 6 per cent silicon.

There is another transformation for iron-carbon alloys; namely, the A_0 transformation, as it is called by Honda, which, at least by the ordinary methods, cannot be found thermally, but which is easily observed magnetically. This occurs at a little over 200°C., and is the point at which pearlite loses its magnetism. This transformation furnishes a means of determining the presence of pearlite and its amount, at least approximately.

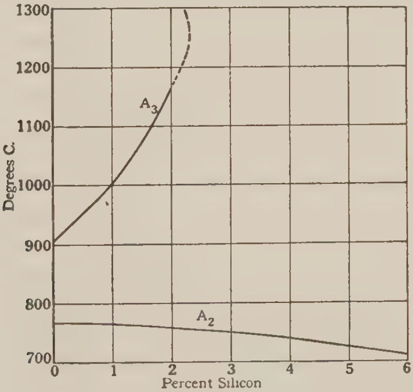

FIG. 93.—Iron-silicon equilibrium diagram for zero carbon.

Silicon has a powerful effect on some of the transformation points, as shown by Figs. 90 to 94, taken from some unpublished data due to Pilling and Halliwell. These silicon-iron diagrams are of special interest, since so much material used for magnetic purposes contains appreciable percentages of silicon. The two most striking effects of silicon, perhaps, are the large increase in the A_3 point and the disappearance of this point at about 2 per cent silicon. If this transformation actually is suppressed, it means that 2 per cent or more of silicon prevents the structural change of iron from the body-centered to the face-centered form. In connection with this change of structure, Fig. 95, due to Weiss and Foëx[3] is of particular interest. This shows that, were it not for the structural change, the alterations in magnetic intensity with temperature apparently would be a continuous function of

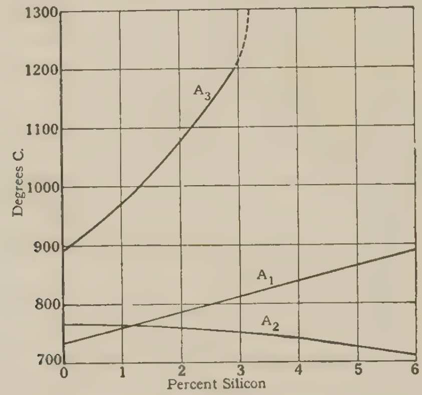

Fig. 94.—Iron-silicon equilibrium diagram for 0.05 carbon.

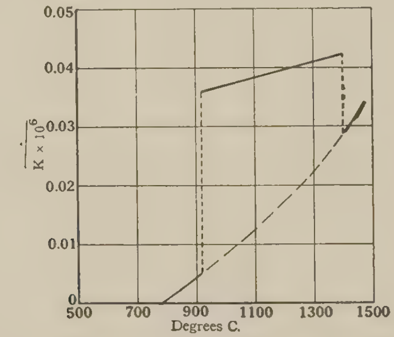

Fig. 95.—Reciprocal of susceptibility against temperature.

the temperature, instead of being discontinuous as is the case for low-silicon materal.

A point of interest in the iron-carbon diagram is the fact that the A_1 and A_2 points change their positions relative to each other for the higher silicon contents, the A_1 becoming the higher. At 1 per cent silicon, they practically coincide. The A_2 transformation is so much stronger that, except by careful work, the A_1 transformation cannot be found experimentally.

Sauveur has given a very good picture of the structural changes which take place with different heat-treatments.[4] Figure 96 refers to eutectoid steel (0.85C.). If the material is cooled slowly from above the critical range, as shown by I, it is first in the austenitic state, which consists of carbon dissolved in iron. It is next transformed into martensite which is Fe_3C dissolved in iron. Next, troostite and then, sorbite are formed. These are not very definite structures, since they consist of mixtures of martensite and pearlite in various proportions. Finally, all of the martensite is converted into pearlite which is usually a lamellar structure consisting of cementite and ferrite or pure iron in definite proportions. For other than 0.85 carbon, there is an excess of ferrite or cementite. Now, if the material is cooled very rapidly, namely, quenched in water, the transformation proceeds only to the martensitic stage (see Fig. 96, II), since the further transformations require more time at an elevated temperature. If, after quenching, the material is heated slowly (see Fig. 96, III), the martensite gradually changes to troostite, then to sorbite,

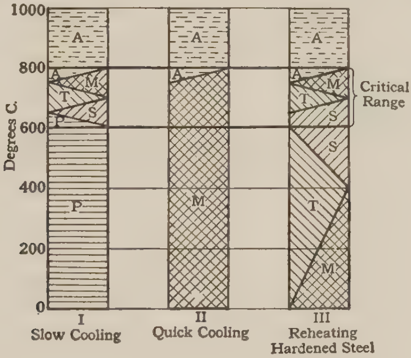

FIG. 96.—Effect of rate of cooling on constituents of eutectoid steel (0. 85 carbon), (Sauveur).
A, austenite; M, martensite; T, troostite; S, sorbite; P, pearlite.

back to troostite, to martensite and, finally, to austenite. It is obvious that, by cooling at a rate between I and II, the material may be left in the troostitic or sorbitic state, though the result will not be quite the same as it would be if the same state were reached by quenching and drawing, as in Fig. 96, III.

Honda[5] has recently given a slightly different set of diagrams for the same effects. According to him, with a rapid quench, Fig. 97, the transformation from austenite to martensite does not begin until a temperature of approximately 300°C. is reached and the transformation proceeds as indicated by *b*. For a slower quench, such as an oil quench, the martensitic state is reached at a higher temperature (see *c*), with a later formation of troostite. For a still slower rate of quenching (see *d*), sorbite may be finally formed with the martensitic and troostitic structures occurring at higher temperatures. For very slow cooling (see *a*), pearlite is formed.

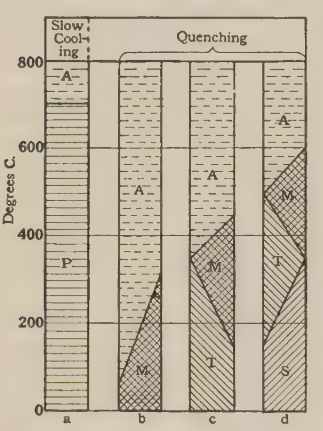

FIG. 97.—Effect of rate of cooling on constituents of steel (Honda). *a*, slow cooling; *b*, rapid quench; *c*, medium quench; *d*, slow quench.

Relation between Structure and Magnetic Properties of Carbon Steel. These various constituents have different magnetic and mechanical properties. Austenite is practically nonmagnetic and is comparatively soft mechanically. The permeability of martensite at high magnetizing forces is only about two-thirds that of pure iron, and at low magnetizing forces it is very poor, as shown in Fig 99. It is very hard mechanically and has a high coercive force. In martensite the carbon is in solid solution in the iron. In troostite the carbon has been precipitated in the form of fine particles of cementite. In this form, then, the induction at high magnetizing forces approaches that of pure iron, and at low magnetizing forces, the permeability increases due to the presence of free ferrite. The coercive force is also lower. Going through sorbite to pearlite, the maximum induction decreases and the permeability for low magnetizing forces increases. At the same time, the coercive force continues to decrease. Pearlite is considerably softer mechanically than martensite. Pearlite has a lower permeability at high inductions, due probably to the fact that cementite saturates at a very low induction, thus causing high flux densities in the parallel ferrite material and therefore a quicker saturation for that constituent; or, if the cementite and ferrite laminations are in series, magnetically, the saturation of the cementite considerably increases the reluctance of the magnetic path. Or, it may be simply considered that for high flux densities the presence of the magnetically saturated cementite may cause the flux to take a longer path in passing from one portion of the material to the next.

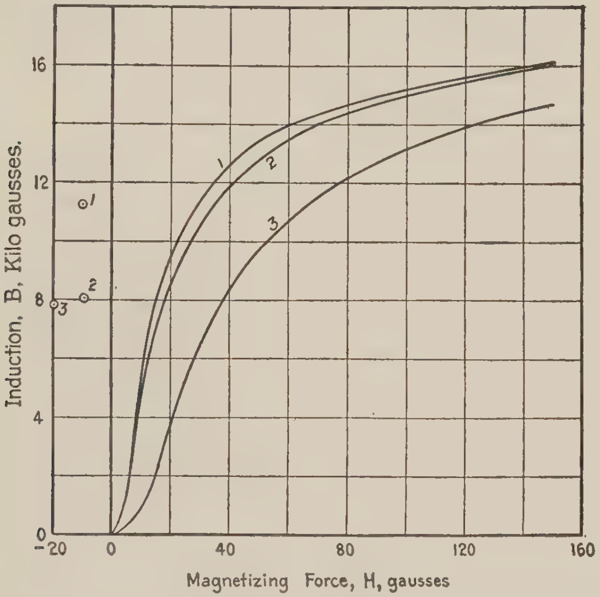

FIG. 98.—Normal induction and hysteresis data for carbon steel.

1. Annealed; 2. quenched in water from below the critical point; 3, quenched in oil from above the critical point. $H_{max} = 150$. The analysis of this steel—carbon, 1.04 per cent; manganese, 0.34 per cent; phosphorous 0.047 per cent; sulfur, 0.038 per cent; silicon, 0.017 per cent.

It is seen then, that these various structures have their own magnetic characteristics, and these relations are very valuable, especially in connection with magnetic analysis. A consideration of these facts will also show why permanent-magnet steel is quenched; and why the core material for electrical apparatus is annealed when the magnetic reluctance and hysteresis losses are desired to be a minimum.

Now, when alloying elements, such as chromium, manganese, nickel, etc., are introduced the transformations of iron-carbon alloys are profoundly altered, not qualitatively, but with reference to the time-temperature effects. These elements tend to slow up the transformations as the material is cooled. If sufficient manganese is present, for instance, even slow quenching may still leave the steel in a partly austenitic condition, namely, much less magnetic than for even the most rapid water quench of plain carbon steel. Without the chromium present, the steel would retain practically none of the material in the austenitic state. It is such an action as this that makes possible the production of a nonmagnetic iron or steel as described previously.

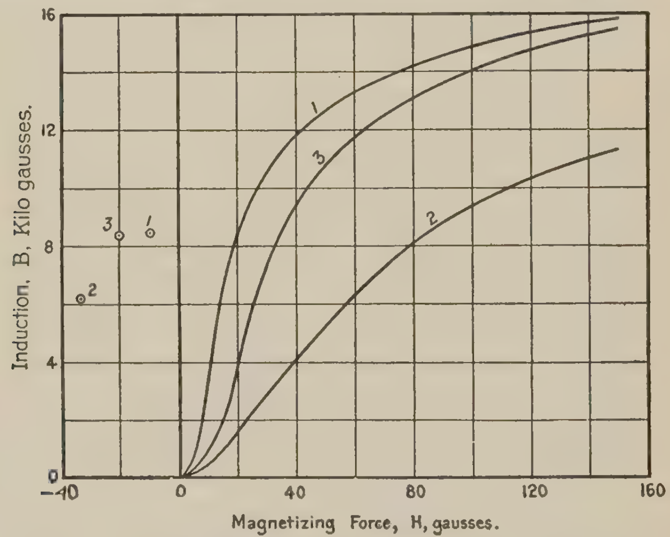

FIG. 99.—Normal induction and hysteresis data for carbon steel. 1, as received; 2, quenched in water from above the critical point; 3, quenched in oil from above the critical point. $H_{\text{max}} = 150$.

These effects will be best brought out by some concrete examples. For much more complete data than can be given here, see the results of Burrows, Fahy, and Nusbaum.[6,7]

Some interesting data are given by Burrows and Fahy for a plain carbon steel containing 1.04C and 0.34Mn as shown by Figs. 98 and 99. In addition to the magnetization curves, it will be noted that the circles at the left show by their vertical height the Br values for $H_m = 150$, and by their distance to the left of the zero line the H_c values for the same maximum H. It is stated by the authors that, in order to obtain hardening, a minimum temperature of 720°C. must be attained. Pilling's diagram, Fig. 89, shows that the critical temperature for this material is 730°C. If cooled from a higher temperature, however, due to the time lag, it might be possible to go even below 700° and obtain a good quench. Figure 98 shows that a quench from below the critical point, even in water, has a much less effect on the magnetic properties than an oil quench from above the critical point. It should be remembered that a water quench is much more drastic than an oil quench for the same temperature, since the former causes more rapid cooling and this tends to retain the material in its high-temperature state.* Figure 99 brings this out very clearly.

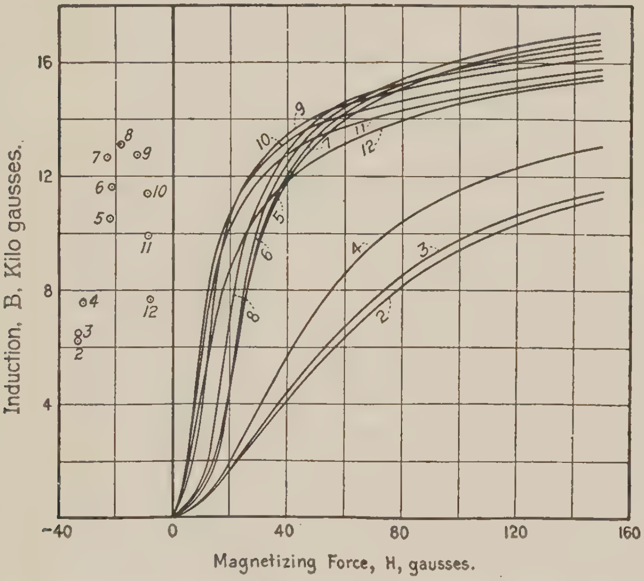

FIG. 100.—Normal induction and hysteresis data for water-quenched carbon steel. All curves quenched from 800°. 2, Not drawn; 3, drawn to 100°; 4, to 200°; 5, to 300°; 6, to 400°; 7, to 500°; 8, to 600°; 9, to 700°; 10, to 750°; 11, to 800°; and 12, to 950°. $H_{max} = 150$.

Low maximum permeability and high coercive force, in general, though not without exceptions, indicate a material which is hard mechanically and magnetically. A notable exception to this is austenitic steel, which has very poor magnetic characteristics. It is, however, comparatively soft. Plain carbon steels do not occur in the austenitic state at room temperature, but some alloy steels do. This is one cause for caution in the use of magnetic criteria for the indication of mechanical properties.

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* There are some exceptions in the case of alloy steels.

Typical results for the magnetic effects due to the quenching of carbon steels are shown in Figs. 98 and 99. Typical results for the effect of drawing on the same carbon steels water-quenched are shown in Fig. 100, also due to Burrows and Fahy. It will be noted that, for high magnetizing forces, the induction increases with drawing temperature up to 400°C. and then drops off again. For the maximum induction for lower magnetizing forces, the drawing temperature has to go to 750°C. The H_c values steadily decrease with drawing temperature, but the B_r values reach a maximum for 600°. It is evident, then, that the heat-treatment required to give a maximum or minimum value for a particular magnetic property is different for different magnetic quantities, and even for different ranges of the same magnetic quantity. It is also evident that wide variations in the magnetic properties of a given material may be obtained by a suitable manipulation of quenching temperature, quenching medium, and drawing temperature. The reasons for these various magnetic effects may be seen from a consideration of the various metallographic changes previously described.

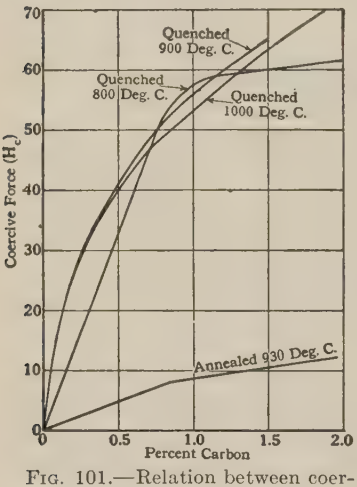

Fig. 101.—Relation between coercive force and carbon percentage for steel (Gumlich).

The relation between carbon content and saturation induction B_s for pure iron-carbon steels, as affected by annealing and quenching, is shown in Fig. 46, due to Burrows. The variation of coercive force with carbon content for different heat-treatments is shown in Fig. 101, due to Gumlich. In the annealed condition H_c is small, indicating a soft material. The steel is in the pearlitic conditions. The point of discontinuity at 0.85 C is significant. At 0.85C the material consists entirely of pearlite. For a smaller percentage of carbon free ferrite is present and the less the carbon the more free ferrite. This is magnetically the softest constituent of steel. In fact, as shown by Yensen, pure ferrite probably has nearly if not quite zero coercive force. Above 0.85C there is an excess of cementite and H_c continues to rise but not as rapidly, because there is no longer any free ferrite to be converted to pearlite or cementite.

The 800-degree quenched material is especially interesting, showing an even sharper break at 1.0C. The coercive force increases linearly and very rapidly with carbon content up to 1.0C, and from there on there is no further increase. This may be explained by referring to the iron-carbon diagram, Fig. 88, where it will be seen that as the carbon increases up to the eutectic point, more and more cementite and less ferrite are present. Cementite is a much harder material than ferrite magnetically, and therefore H_c increases with carbon content. Above the eutectic point the material is all in the cementitic form, and therefore H_c shows no further increase with carbon content. With higher quenching temperatures, however, there is a somewhat different condition. It will be seen from the iron-carbon diagram that the higher the temperature the greater the carbon percentage before the *Acm* line or cementite transformation is reached. This means that when quenching from the higher temperatures more carbon is held in solution, thus giving a higher coercive force Below 0.85C, of course, this effect does not occur. Evidently, the internal strains, as well as the structure, would have to be considered for a complete explanation of these magnetic effects.

The effect of drawing on some of the magnetic properties of a water- and oil-quenched 1 per cent carbon steel is shown in Fig. 102, due to Nusbaum. He explains these results in this way: The water-quenched specimen probably consists of nearly pure martensite; in other words, it consists of cementite, which is one-tenth as magnetizable as iron, dissolved in ferrite. This dissolved cementite greatly decreases the intensity of magnetization of the ferrite. Now, by applying the drawing temperature, the cementite is allowed to precipitate out, and at about 400°C. this process is complete, giving the maximum induction. With further increase in temperature, the material passes through the other forms, troostite, sorbite, etc., to the annealed condition. In the last condition the ferrite has been recombined into the pearlitic state, with a corresponding decrease in B_m, since pure ferrite is more magnetizable than iron in any other form (except when nickel or cobalt is present). Beyond the annealing temperature, according to Nusbaum, the only effect is a coarsening of the structure, with a corresponding decrease in B_r but very little effect on H_c. The maximum value of B_r corresponds quite closely with the transformation point between troostite and sorbite.

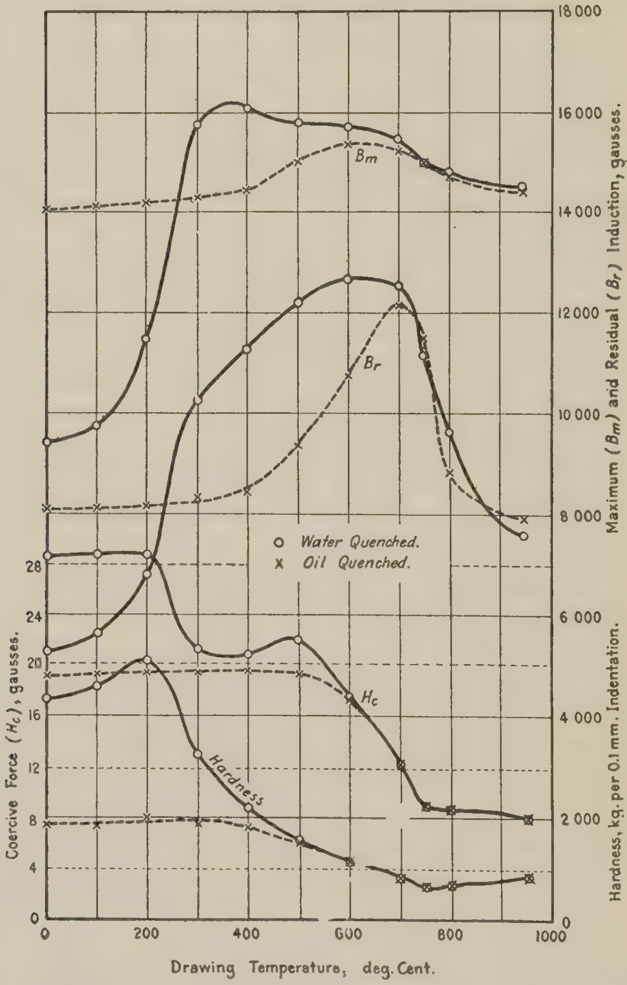

FIG. 102.—Effect of heat-treatment on the maximum induction B_m, residual induction B_r, coercive force H_c, and the mechanical hardness of a 1 per cent carbon steel.

The oil-quenched specimen indicates that the rate of quenching is not sufficiently rapid to prevent the precipitation of most of the cementite. The lower drawing temperatures, then, have very little effect. In fact, not until 400°C. is reached does the effect of drawing begin to become marked. After passing into the sorbitic state, at about 700°, the oil- and water-quenched materials are practically identical.

It is evident that by varying the rate of cooling from the quenching temperature, somewhat the same condition may be obtained as by quenching rapidly and drawing. The final result, nevertheless, is appreciably different, in general, in the two cases. In other words, a troostitic material obtained by rapid quenching and drawing is different from a troostitic material obtained simply by slower quenching with or without a subsequent drawing. These differences are partly due, at least, to differences in the internal strains.

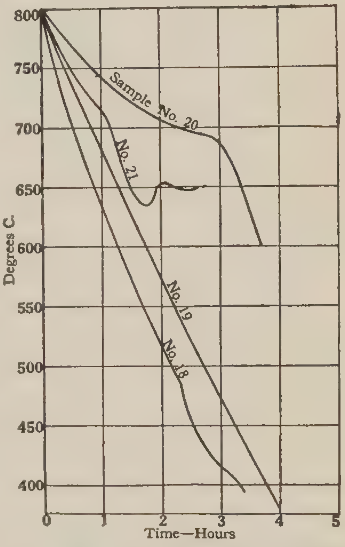

FIG. 103.—Cooling curves for four specimens of annealed eutectoid carbon steel.

Annealing.—The effect of very slow rates of cooling, *i.e.*, annealing, on the magnetic properties of steel is worthy of careful consideration. Nusbaum and Cheney[8] have obtained some very interesting results along this line. The cooling rates used for four samples of a plain carbon steel containing 0.85C, 0.23Mn, 0.23Si, and with the other impurities low are given in Fig. 103. There were also two other samples of the same material, No. 16 which was air-cooled, and No. 17 which was cooled in lime. These samples had all been previously annealed at 800°C. The magnetization curves for the six samples are given in Fig. 104, and the corresponding permeability curves in Fig. 105. Table XV shows the collected data. It will be seen that the rate of cooling has an appreciable effect on the magnetic properties; even though it is as slow as shown by the range of Fig. 103, the slower the cooling, the softer is the material magnetically.

From Table XV, it will be seen that the coercive force, maximum permeability, and resistivity line up well with the rate of cooling; but the residual induction is not so definitely affected. These magnetic differences with different rates of cooling are due to structural differences resulting from those rates, as may be seen from microscopic analyses. In the air-cooled specimen (No. 16), the material is largely sorbitic, with patches of pearlite. As the cooling rate becomes slower, the material becomes pearlitic and for the slowest cooling rate (No. 20), the divorced pearlite or spheroidal state is being approached.

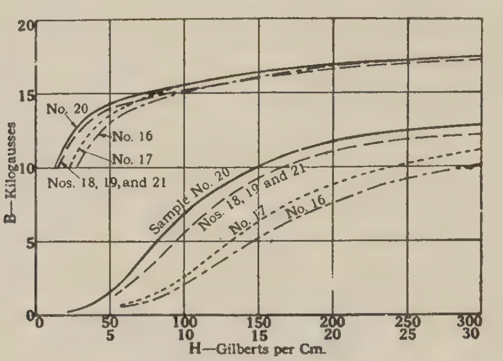

FIG. 104.—Effect of cooling annealed eutectoid carbon steel upon magnetic induction for small and intermediate magnetizing forces.

The reluctivity curves for these samples are given in Fig. 106. They show a decided break, which indicates that there are two different magnetic constituents, ferrite and cementite. This break, moreover, occurs at lower magnetizing forces, as the rate of cooling is lowered. The saturation values are given by the reciprocal of the slopes of these curves, as shown by the two sets of figures in Table XV. The true saturation is the higher value as given by the upper half of the reluctivity curves. The apparent saturation is given by the lower half.

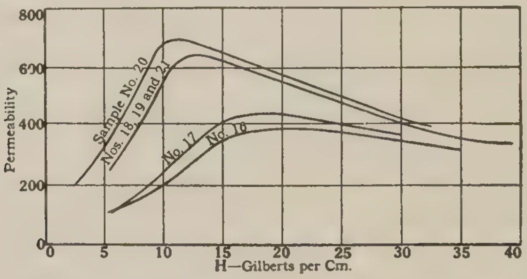

FIG. 105.—Effect of rate of cooling eutectoid carbon steel upon permeability.

TABLE XV.—EFFECT OF COOLING ON MAGNETIC CHARACTERISTICS

Specimen number	Time held at 800°C.	Method of cooling	Time cooling from 800 to 650°C.	Maximum permeability, μ_m	Magnetic induction B			Residual induction $H_m = 150$ B_r	Coercive force $H_m = 150$ H_c	Saturation intensity (calculated) J_s	Scleroscope hardness	Resistivity ρ
					$H = 15$	$H = 150$	$H = 1000$					
	Minutes		Minutes		Kilogausses	Kilogausses	Kilogausses	Kilogausses	Gilberts per centimeter	C.g.s. units		Microhms
16	..	Air cooled	...	385	5.15	16.10	20.05	10.05	13.4	1564 1520	43.3	0.2025
17	..	Lime cooled	...	437	6.15	16.30	20.00	10.54	12.4	1550 1500	42.3	0.2006
18	12	Furnace cooled	56	630	9.30	16.10	20.03	12.30	10.18	1580 1490	33.0	0.1941
19	13	Furnace cooled	78	630	9.30	16.10	20.03	12.30	10.00	1600 1430	30.4	0.1950
20	20	Furnace cooled	200	698	10.00	16.30	20.03	12.36	9.2	1610 1430	29.9	0.1931
21	13	Furnace cooled	90	633	9.30	16.10	20.08	11.97	9.2	1540 1400	33.6	0.1963

These results are summarized as follows by the authors:

1. With decrease in the cooling rate, there is a marked increase in the value of the maximum induction for a given value of the magnetizing force, an increase in the magnitude of the maximum permeability, and a decrease in the magnitude of the coercive force.

2. As the structure is changed from an essentially sorbitic one, through lamellar pearlite to divorced pearlite, there is a gradual shifting of the break in the reluctivity line toward the origin. Also, the difference between the magnitudes of the real and apparent values of the maximum intensity of magnetization is greatest when the structure is that of lamellar pearlite.

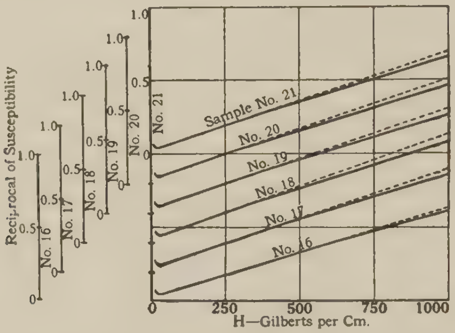

FIG. 106.—Effect of rate of cooling annealed eutectoid carbon steel upon reciprocal of susceptibility.

3. There is a marked agreement between the values of the coercive force and the scleroscope hardness, as influenced by the various cooling rates, except when the specimen is held at a temperature of 650°C. for a definite time.

For other carbon contents, there is an endless variety of possible results, but these will serve to indicate the general nature of the effects.

Alloy Steels.—The effect of certain alloying elements added to carbon steels may be profound. Those elements which do have a profound effect, such as manganese, nickel, chromium, etc., usually act not to change essentially the nature of these transformations which have just been described, but simply to slow them up; thus, requiring a slower cooling rate to effect the given transformation, or, in some cases, as for silicon, some of the transformations may have their temperatures appreciably changed or may be suppressed altogether.

To show these effects compare Figs. 107 and 108. Figure 107 is for a plain carbon steel quenched in oil from 800°C. It is, in fact, the same material as given for Fig. 100, but, in the case of Fig. 100, the material was quenched in water. The material of Fig. 108 was also quenched in oil from 800°, but this is an alloy steel, the essential constituents being 0.64C, 0.51Mn, 0.21Si, 0.63Ni, and 0.58Cr, the rest of the impurities being low.

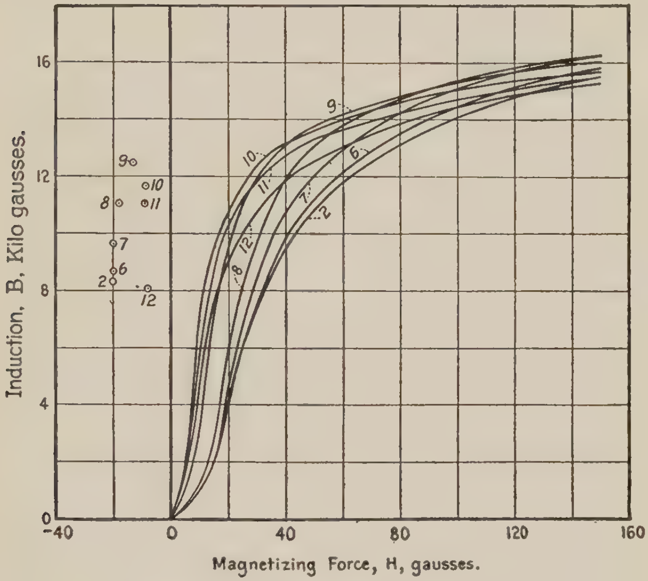

FIG. 107.—Normal induction and hysteresis data for oil-quenched carbon steel. All curves quenched from 800°C. 2, not drawn; 6, drawn to 400°; 7, to 500°; 8, to 600°; 9, to 700°; 10, to 750°; 11, to 800°; and 12, to 950. $H_{\max} = 150$.

The large difference between Figs. 107 and 108 and the similarity of Fig. 108 (oil-quenched alloy steel) to Fig. 100 (water-quenched carbon steel) should be noted. In the case of the oil-quenched carbon steel, Fig. 107, the cooling was so slow that the material had time to transform to a considerable extent, although further transformation took place due to the tempering process. In the case of the water quench, Fig. 100, for this same plain carbon steel the transformations were far from complete; but, in the case of the alloy steel, even the comparatively slow oil quench did not allow the transformation to go a great way, due to the slowing-up action of the alloying elements, particularly the nickel and chromium. Evidently, however, as indicated by the drawing results, if a still slower quenching medium than oil had been used for the alloy steel, results similar to those of Fig. 107 for the oil-quenched plain carbon steel would have been obtained.

It is interesting to note that for both the carbon and alloy steels the drawing temperature at which the abrupt change in induction takes place is approximately the same; namely, between 200 and 300°C. This means that the temperature and nature of the transformations have not been essentially changed by the alloying elements, but only the time required. Some steels, as for instance the cobalt permanent-magnet steels, have these transformations so slowed up by the alloying elements that they retain their maximum magnetic hardness even when cooled in air. This is also true of high-speed tool steels, though in this case for the best results the cooling has to be somewhat hastened by using an air blast.

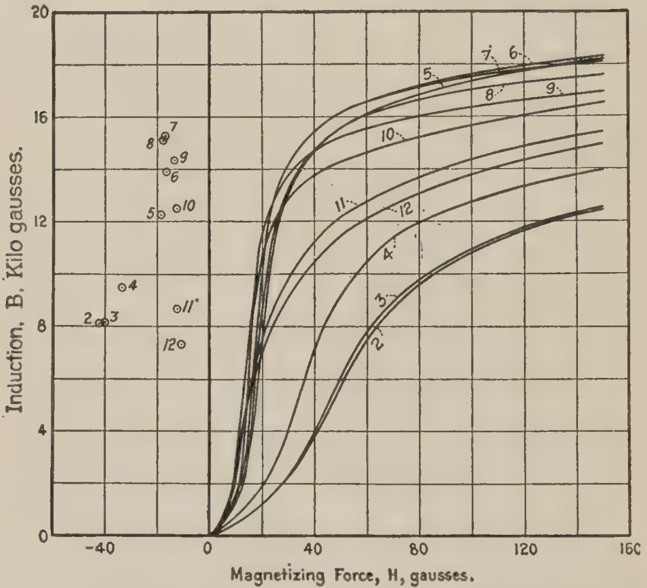

Fig. 108.—Normal induction and hysteresis data for oil-quenched alloy steel. All curves quenched from 800°C. 2, not drawn; 3, drawn to 100°; 4, to 200°; 5 to 300°; 6, to 400°; 7, to 500°; 8, to 600°; 9, to 700°; 10, to.750°; 11, to 800°; and 12, to 950°. $H_{\max} = 150$.

Smith, Campbell, and Fink have recently published some interesting results showing the difference between the annealed and quenched properties of carbon and chromium steels with different carbon contents.[9] Figure 109 shows the magnetization curves for the plain carbon series as quenched in water from 915°C. The annealed data are similar but, of course, show higher permeabilities. These samples had carbon contents as shown on the curves, with the other impurities quite low. Figures 110 and 111 show similar curves for the chromium steels. The quenching was from 885°C. The alloying materials were 0.24Mn, 0.25Si, 2.23Cr, and 0.12Ni. The other impurities were low. This composition should be compared with that of chromium magnet steel.* The annealing process consisted simply in allowing the

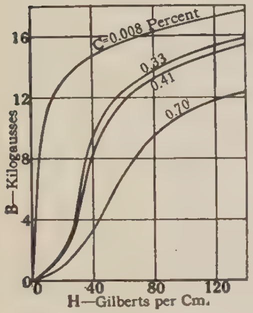

FIG. 109.—Magnetization curves of hardened carbon steels.

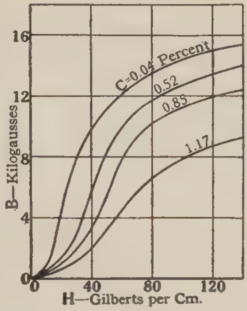

FIG. 110.—Magnetization curves of hardened chrome steels.

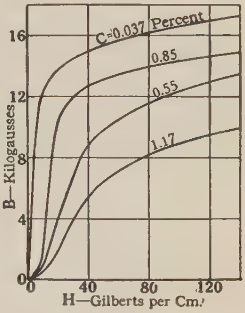

FIG. 111.—Magnetization curves of annealed bars of chrome steel.

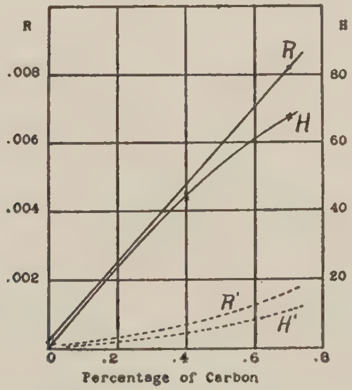

FIG. 112.—Magnetic characteristics of hardened carbon steels. *R* and *H* same as in Fig. 113.

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* See Chap. V.

sample to cool from 950°C. in the furnace, and must have been fairly slow. In spite of this slow cooling, it can be seen that the alloy steels have much poorer magnetic properties than the plain carbon steels. The annealed chromium steels, in fact, are not very different from the hardened carbon steels.

The minimum reluctivity values (the reciprocal of the maximum permeability values) and the *H* values corresponding to maximum permeability for the carbon and alloy steels respectively, both in the annealed and quenched conditions, are shown in Figs. 112 and 113. The practically linear relation between carbon content and *R* and *H* values is interesting. The notable exception for the annealed alloy steel at 0.85°C., Fig. 113, is especially significant. At this carbon percentage the material acts as though it had a much lower carbon percentage. The authors explain this as due to the fact that the chromium combines with the carbon, thus, in effect, removing some of each element from the iron. It is significant that this occurs at the eutectoid carbon percentage.

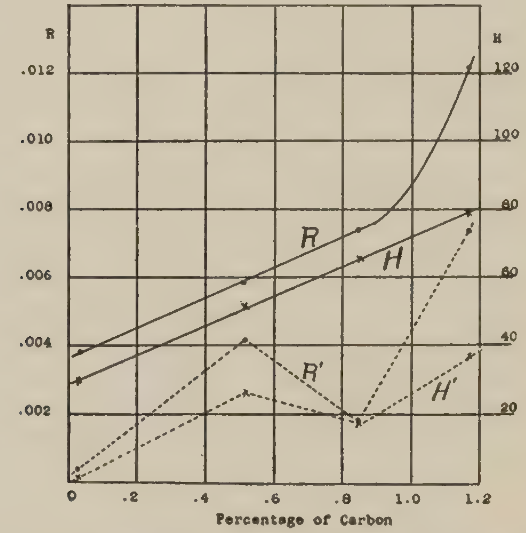

FIG. 113.—Magnetic characteristics of hardened chrome steels.

R shows the minimum values of the reluctivity. *H* shows the values of m.m.f. necessary to bring the steels to the point of maximum permeability. *R'* and *H'* show the corresponding values after the steels have been annealed. Note the drop in these curves at 0.85 carbon.

The nickel-iron series offers some interesting examples of the lowering or even suppression of some of the transformation points down to room temperatures. Figure 114 shows the magnetic transformation temperatures for the whole iron-nickel series as given by Dumas.[10] There are two types of magnetic transformation, one for nickel contents below 30 per cent and the other for nickel contents above 30 per cent. For the low nickel percentages, the alloys lose their magnetism at a much lower temperature on cooling than they regain it on heating. In other words the transformation is irreversible. For the higher nickel percentages, the heating and cooling transformation temperatures are nearly at the same point for a given composition. According to Dumas, when dealing with nearly pure alloys such as he used, there is no nickel-iron compound which is nonmagnetic at room temperatures. If, however, very small percentages of carbon or manganese are present, the magnetic transformation point in the region of 30 per cent nickel may be easily depressed considerably below ordinary room temperatures. The Bureau of Standards[11] has gathered together considerable data on nickel steels, and gives the mean results for these transformation temperatures as shown by Fig. 115, where the temperatures are expressed in degrees Kelvin, or absolute temperature. There is a constant difference of 273° between this temperature scale and the centigrade scale.

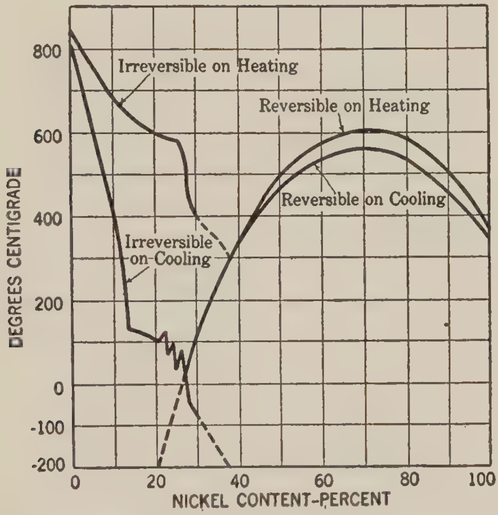

Fig. 114.—Magnetic transformations for iron-nickel alloys.

Table XVI and Figs. 32 and 33* as given by Yensen show the effect of quenching these iron-nickel alloys at −70°C. (CO_2 snow in gasoline), and at −185°C. (liquid air). There are included some similar data as obtained by Honda. Yensen's results were obtained on very pure vacuum-melted alloys. His saturation values are possibly, in some cases, at least, a little high, due to extrapolation from too small magnetizing force values. It will be seen that this low-temperature quenching has a very marked effect near the 30 per cent nickel composition, due to the irreversible transformation, as would be expected from Figs. 114 and 115. For the higher and lower nickel contents the low-temperature quenching has no appreciable affect. It should be noted that the very large increase in saturation induction for the low-temperature quench and the 30 per cent alloy is accompanied by a corresponding decrease in electrical resistivity.

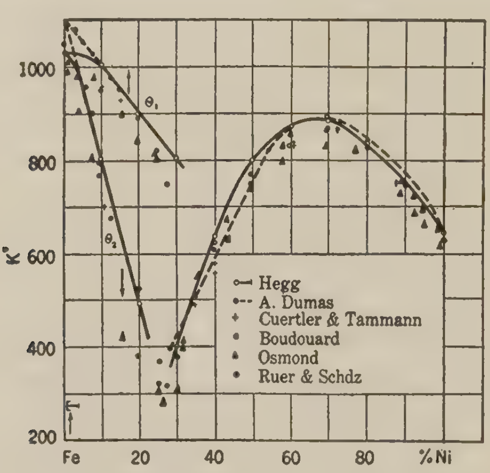

Fig. 115.—Absolute centigrade temperatures of magnetic transformation (Curie points) for pure ferronickels (Hegg).

Yensen comments as follows on these results:

> It will be noted that while there is practically no change in the properties of the 15, 34.5 and 50 per cent alloys, the 30 per cent alloy has undergone a marked change. Its saturation value (B_s) was increased from 2,700 to 14,600 by cooling to −70°, and to 17,800 by cooling to −180°. Similarly, the electrical resistance was decreased from 82 to 38, and to 32 by the above treatments. It is probable that the change

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* See Chap. IV.

would have gone to completion at −70° if the testpiece had been held there sufficiently long, and that the irreversible transformation point, therefore, lies between 0 and −70°, thus confirming Dumas' results.

While only a few points were determined, they are sufficient to demonstrate that the cusp of both curves, after the completion of the transformations, occurs for approximately 34.5 per cent nickel instead of for 30 per cent, as the previous investigation would lead one to believe. This points strongly toward the existence of the compound Fe_2Ni, corresponding to the 34.5 per cent nickel, suggested by earlier investigators. The existence of the compound FeNi, corresponding to 51.5 per cent nickel, is more doubtful, because there is no definite indication of it in the electrical resistance curve.

It is interesting to note that while the saturation value of the 30 per cent alloy was increased to a remarkable extent by being cooled to below the irreversible transformation point, the permeability at low flux densities was decreased and the hysteresis loss enormously increased, the latter 15 times. In other words, the reversible transformation produces a material with low hysteresis loss and low magnetic saturation, while the irreversible transformation produces a material with six times the saturation value but with fifteen times the hysteresis loss. Thermal and magnetic hysteresis thus go together.

It is also interesting to note that there apparently is no change in the microstructure of the 30 per cent alloy accompanying the marked magnetic and electrical transformation. It is therefore apparent that the magnetic and electrical transformations are atomic or ionic in their nature.

A number of interesting articles have appeared from time to time in the *Journal of the Iron and Steel Institute* on the magnetic properties of alloy steels. Figure 116, taken from one of them shows the nature of the irreversible magnetic transformations,[12] of a 25 per cent nickel steel of somewhat less purity than Yensen's material. It will be seen that above 950°C. the relation between magnetic induction for a magnetizing force of 300 gilberts per centimeter is reversible, but below that temperature the effects are far from reversible, as indicated by the arrows. For a drop in temperature from *a* to *b* just below zero, the induction remains almost constant, but below that temperature it rapidly increases to the point *c*, which is that of liquid air. If the temperature is now increased, the induction increases slightly to *d* and then decreases rapidly to zero at *e*. With further increase of temperature the induction returns to the starting point *a*. If, however, at point *f* the temperature is increased, a direction parallel to *cd* is followed to the line *de*, when that line is followed as before.

If, at a point *g*, the temperature is decreased the induction is constant along a vertical line parallel to *ab*. If the temperature is decreased from *e*, a non-magnetic material results. These magnetic changes are tied up with the microstructure. Below 950°C., a considerable temperature range is passed over before a structural change is produced and any considerable magnetic change is thereby effected.

A steel with a manganese content of over 12 per cent, under ordinary conditions, is practically nonmagnetic. A 12 per cent manganese steel, however, may be rendered magnetic under certain conditions, as indicated by Fig. 117.[13] These curves are very similar to those of Fig. 116 indicating that the cause of the changes is similar. This material has an actual manganese content of 11.67 per cent, and a carbon content of 0.29 per cent. Curve 1 is for the material slowly cooled from 750°C.; and curve 2 for the same material quenched from 1200°C. The authors do not give an explanation of these changes, but a knowledge of the atomic structure would probably shed considerable light on the matter. The marked increase in magnetizability after the high-temperature quench is particularly interesting. A 20 per cent manganese steel is hardly magnetic at all, but a liquid-air

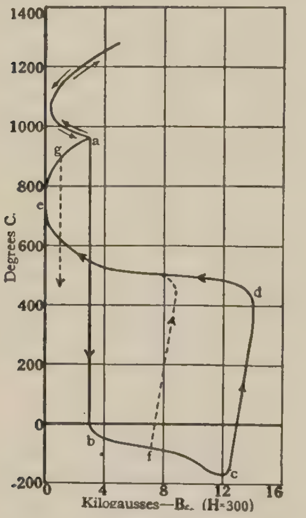

FIG. 116.—Irreversible magnetic transformations for 25 per cent nickel steel.

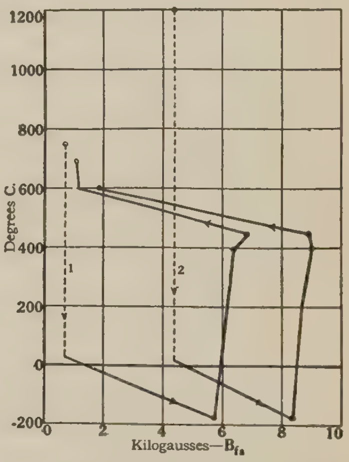

FIG. 117.—Irreversible magnetic transformations for 12 per cent manganese steel.

TABLE XVI.—MAGNETIC AND ELECTRICAL PROPERTIES OF Fe-Ni ALLOYS, REVERSIBLE AND IRREVERSIBLE TRANSFORMATIONS

Condition	Max. permeability, μ_m	Flux density for μ_m, gausses	Flux density (kilogausses) for H (gilberts per centimeter) of				Saturation value, B_s	Hysteresis loss for B = 10,000—ergs per cubic centimeter per cycle	Electrical resistance—microhm-centimeters	Max. permeability, μ_m	Flux or density for, μ_m, gausses	Flux density (kilogausses) for H (gilberts per centimeter) of				Saturation value, B_s	Hysteresis loss for B = 10,000—ergs per cubic centimeter per cycle	Electrical resistance—microhm-centimeters
			1	10	100	400						1	10	100	400			
	30 per cent Ni (2 Ni 232) rings									34.5 per cent Ni (2 Ni 234) rings								
Annealed at 1100°C. in vacuum	560	220	0.4	1.5	2.8	....	......	....	..	2,210	1,500	2.0	7.2	11.21				
Cooled to −70°............	...	.....	...	...	....	....	......	....	..	.....	.....	0.5	5.3	13.1				
Cooled to −70° and heated to +20°....................	232	4,650	0.1	2.0	10.3	....	......	....	..	.....	.....	2.1	7.0	11.1				
Cooled to −185°............	279	5,580	0.1	2.3	13.0	....	......	....	..	.....	.....	0.3	5.3	13.4				
Cooled to −185° and heated to +20°....................	244	4,880	0.1	1.9	12.0	....	......	....	..	.....	.....	0.6	4.7	11.2				
	30 per cent Ni (2 Ni 232) rods									3.45 per cent Ni (2 Ni 233 and 234) rods								
Annealed at 900°C. in vacuum.	500	250	0.4	1.5	2.6	3.1	2,700	2,230*	82	3,200	1,300	2.7	8.0	11.7	12.0	11,500	1,000	81
Cooled to −70° and heated to +20°....................	213	4,550	0.1	1.8	10.2	13.4	14,600	31,100	38	.....	.....	2.6	7.7	11.6	12.0	......	.....	80
Cooled to −185° and heated +20°....................	250	5,750	0.1	1.8	12.5	16.4	17,800	....	32	3,120	1,560	2.6	7.6	11.7	12.1	11,710	.....	78
	15 per cent Ni (2 Ni 225) rods									50 per cent Ni (2 Ni 261 and 262) rods								
Annealed at 900°C. in vacuum	460	3,000	0.2	4.9	17.3	21.0	21,600	12,500	30	9,600	2,870	6.8	13.0	15.4	15.6	15,200	810	44
Cooled to −70° and heated to +20°....................	494	3,600	0.2	4.8	17.2	21.0	......	....	30	.....	.....	6.8	12.9	15.2	15.5	......	.....	44

* Calculated from the loss for B = 2,000 by means of the 1.6 law; $W_{10} = W_2(10/2)^{1.6}$.

quench makes it slightly magnetic, the effect evidently being the same as for the 12 per cent manganese steel, but of different degree. The fairly high magnetizability of the 12 per cent manganese steel after a 1200° quench is particularly remarkable, since the material seems to be austenitic, and, in general, it is considered that austenitic steel is nonmagnetic.

In the discussion of nonmagnetic steels, it has been shown that manganese and chromium have effects similar to those of nickel in depressing the transformation points. The above data on iron-nickel alloys, however, serve to show the nature of the effects. Some of these nonmagnetic steels sometimes will be rendered magnetic by strains beyond the elastic limit. In order to make them nonmagnetic again, they must be put through the proper heat cycle. Again, it sometimes may be found that annealing will cause a nonmagnetic sample to become magnetic. This is often caused by a selective oxidation, where one of the constituents of the alloy is removed by the oxidation process to a greater extent than the others. This alters the composition of the alloy on the surface, giving a magnetic scale. Machining of the surface will again render the material nonmagnetic.

These irreversible high-temperature magnetic effects may be summarized as follows: The constitutional changes which are produced in iron-carbon alloys are accompanied by more or less definite changes in the magnetic properties. If the structure or previous heat-treatment of the material is known, a fair estimate of the magnetic properties may be made; or, if the magnetic properties are known, a reasonably reliable guess at the structure may be made. The chemical composition of the material in question must be known, of course, at least approximately. If an alloy steel is quenched rapidly enough to leave it in the austenitic state, it will be nonmagnetic. If the rate of quenching is less rapid, martensite will be formed. (A plain iron-carbon alloy, in general, cannot be quenched with sufficient rapidity to leave it in the austenitic state.) Martensite is characterized, magnetically by low permeability at all magnetizing forces, low retentivity, and high coercive force. If the quenching is slower, or if the material is drawn sufficiently, troostite will be formed. This has high permeability at high inductions, but rather low permeability at moderate or low magnetizing forces. The retentivity is higher than for martensite, but the coercive force considerably lower. With a still lower rate of quenching, or higher drawing temperature, sorbite is formed, which has a slightly lower permeability than troostite at high inductions, but a little higher permeability at low magnetizing forces. The retentivity is about a maximum at the transition point between troostite and sorbite. The coercive force for sorbite is slightly lower than for troostite. Annealed or slowly-cooled material is in the pearlitic state, and is characterized by considerably lower permeability at high inductions than for troostite, but much higher permeability at low magnetizing forces. The retentivity of pearlite is lower than for troostite. The chief characteristic of pearlite is low coercive force.

Alloying elements act not only to slow up the transformations, or to suppress them, but have a definite effect on the magnetic properties as well. Even though the annealing is done very slowly, chromium, manganese, or nickel, for instance, in general, will reduce the permeability and raise the coercive force for a given carbon content. In this matter of heat-treatment, time is almost as important as temperature. The magnetic characteristics of a given specimen of a given chemical composition may be known perfectly for a definite heat-treatment, but it will be impossible accurately to predict the results for another piece of the same material having different dimensions, because the quenching rates will be different. This means not only that the transformation of the new piece, if it has a larger cross-section, will proceed more slowly and therefore further, but that the internal strains due to quenching may be quite different; and, as shown previously, strains may produce very considerable changes in magnetic quality. Practically, it is necessary to study the effect of heat-treatment on the particular size and shape of sample in which one is specifically interested.

The actual reasons for the effect on the magnetic properties of the structural changes have not been considered to any extent, partly because it is beyond the province of this discussion, and partly because it is still largely a subject for speculation. For a given theory of magnetism, a more or less adequate explanation of these effects may be given, but so far, there appears no satisfactory theory of magnetism.

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CHAPTER X

EFFECT OF TEMPERATURE

Under this heading will be considered only reversible-temperature changes, as distinct from permanent temperature effects as discussed in the previous article. Low-temperature effects are chiefly of importance with reference to permanent-magnet steels, when used in connection with electrical measuring instruments. High-temperature effects produce enormous changes in the magnetic properties of ferromagnetic materials.

Low-temperature Effects.—To determine the effect of temperature on the accuracy of measurement of the magnetic properties of commercial materials, the Bureau of Standards a few years ago determined the magnetic temperature coefficients for a number of different materials as indicated by Tables XVII and XVIII.[1]

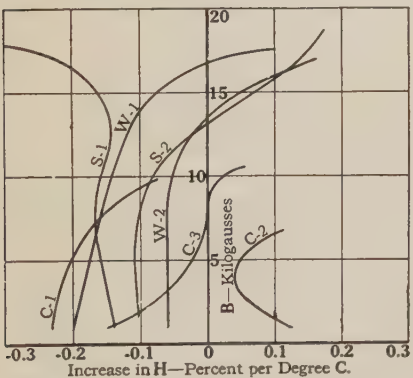

FIG. 118.—Percentage change in magnetizing force for a given induction due to a 1° rise in temperature.

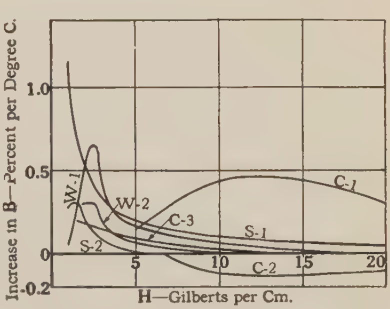

FIG. 119.—Percentage change in induction for a given magnetizing force due to 1° rise in temperature.

The percentage changes in magnetizing force for a given induction due to a 1° rise in temperature are given in Fig. 118; and Fig. 119 shows the percentage changes in induction for a given magnetizing force due to a 1° rise in temperature. These values are based on measurements made at 3, 25, and 88°C. It is interesting to note that the temperature coefficient of the same material in some cases may be either positive or negative, depending on the previous heat-treatment. It was necessary to age these samples before determining the temperature coefficients, since at the higher temperatures quite appreciable permanent decreases in permeability occurred. Sanford reaches the following conclusions:

TABLE XVII.—CHEMICAL COMPOSITION

	C	S	P	Mn	Si
Cast iron	3.65	0.074	0.656	0.52	1.57
Wrought iron	0.053	0.028	0.155	0.15	0.15
Low-carbon steel	0.073	0.036	0.100	0.33	0.10

TABLE XVIII.—HEAT-TREATMENT

Designation	Material	Heat-treatment
C—1	Cast iron	As received
C—2	Cast iron	Quenched from 1000°C.
C—3	Cast iron	Annealed at 900°C.
W—1	Wrought iron	As received
W—2	Wrought iron	Annealed at 900°C.
S—1	Low-carbon steel	As received
S—2	Low-carbon steel	Annealed at 900°C.

1. The temperature coefficient of magnetic permeability, though small, cannot be neglected in magnetic measurements of high accuracy.
2. On account of the wide variations in temperature coefficient, not only for different materials, but also for the same material with different heat-treatments, corrections cannot be made to standard temperature from data obtained from other materials.
3. Unless the temperature coefficient is known for the particular material under test, temperature control offers the only means of avoiding the error due to temperature changes, at least where errors as great as 1 per cent are to be avoided. Conditions often arise in practice where the temperature of a specimen may be raised from 10 to 20° above the temperature of the room, due either to a comparatively heavy current or to the use of coils already heated from a previous test. Since temperature coefficients may be as great as 0.3 per cent per degree, errors amounting to 2 per cent or more may exist.

The magnetic-permeability temperature coefficients of commercial electrical sheet show some rather interesting variations. A knowledge of these temperature coefficients is of value not only in connection with the variations which may result in the

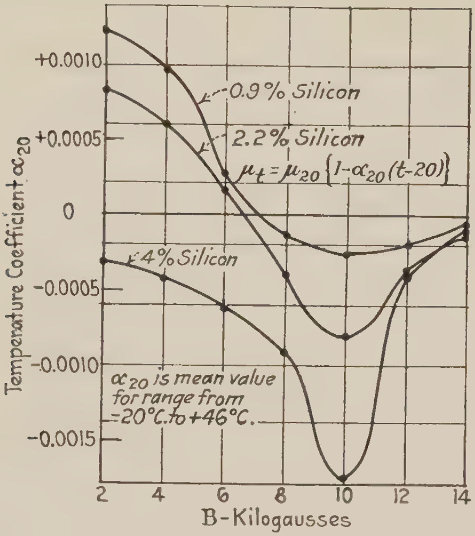

FIG. 120.

process of testing, but more particularly due to the fact that these materials are used for the cores of several types of electrical measuring instruments, both indicating and integrating. The temperature-permeability variations of the core material may affect appreciably the accuracy of reading of watt-hour meters.

An investigation of the temperature coefficients of low-, medium- and high-silicon sheet[2] showed that the variation of permeability between −20 and +46°C. was practically linear for a given induction. The 20° permeability-temperature coefficients as a function of induction are given by Fig. 120. Each of these curves shows the mean results for several samples.

This investigation yielded the following conclusions:

1. Low- and medium-silicon steels have large positive permeability-temperature coefficients for low inductions, and negative coefficients for high inductions (up to 14 kilogausses). Four per cent silicon sheet on the average has negative coefficients for all inductions (up to 14 kilo-

gausses), though individual samples may have small positive coefficients for low inductions.

2. As the silicon content increases, the coefficients tend to move in a negative direction. This may be due to the direct influence of the silicon, or to an indirect influence of the silicon on the carbon and other impurities.

3. The shape of the temperature coefficient curves seems to be much more definitely a function of the induction than of the m.m.f., since the maximum negative temperature coefficients correspond very definitely to a certain induction, but may vary over a considerable range of m.m.fs.

4. There seems to be no definite relation between permeabilities and temperature coefficients for the individual samples of a particular grade of material and no definite relation between the inductions at which maximum permeabilities and maximum temperature coefficients occur.

Permanent magnets, in general, suffer a diminution of magnetism as the temperature rises, although this effect is small until temperatures of 100°C. or more are reached. Christie states that the loss of magnetism is not a linear function of the temperature, but its rate increases with the temperature. For room-temperature ranges, this temperature coefficient for chromium and tungsten magnets, as used in electrical measuring instruments, is assumed to be about -0.5 per cent per degree centigrade. This effect is a very useful one in the case of the damping magnets of watt-hour meters, since it largely compensates for the decreased torque due to the higher resistance of the windings. More detailed data on the temperature coefficients of permanent-magnet materials are given in chapter V.

The effect of liquid-air temperatures on magnetic properties, while of little commercial importance, is of interest from a theoretical standpoint. E. M. Terry makes the following statements in regard to this effect:[3]

> With the advent of liquid air, Fleming and Dewar, in 1896 studied the changes which are produced in the magnetic qualities of Swedish iron at low temperatures. In annealed specimens, they found the permeability for all fields less at low temperatures, while for unannealed and hardened iron, it increased as the temperature was lowered, the effect being greater with hardened iron. The hysteresis loss was independent of the temperature. More recently, Honda and Shimizu[4] found, for Swedish iron cooled in liquid air, that the permeability and hysteresis loss decreased for small fields, but increased for large. These results have been confirmed by Waggoner[5] for low-carbon iron.

These low-temperature effects are small, the differences being in general only a few per cent from the room-temperature values. Data (unpublished) on a sample of 4 per cent silicon-steel sheet indicate an increase in saturation value of about 3 per cent and an increase in hysteresis loss of about the same amount.

High-temperature Effects.—When iron or steel is subjected to an increasing temperature, in addition to gradual changes in the magnetic properties, there are also more or less abrupt changes at certain definite temperatures, depending on the chemical composition, in most cases carbon being the chief determining factor. When carbon is present there is usually a definite but small change at a little over 200°C., the A_0 point. This decrease in permeability is nearly reversible with temperature. This effect is due to the presence of cementite which, as shown by Honda, loses its ferromagnetic properties in this temperature region. Figure 121 as given by Honda,[6] is typical of this type of change. As the silicon increases above 5.5 per cent, the A_0 point disappears, showing that cementite no longer exists for the high-silicon contents. With increasing silicon, the A_1 point occurs at higher temperatures, but beyond 4.5 per cent silicon it is not discernible, as it increases beyond the A_2 point. For the medium-silicon percentages, there is a reversible transformation at about 450°C., due to a solid solution of Fe_3Si_2 and carbide. With higher silicon percentages the A_2 point gradually decreases and overlaps the solid solution change. For samples containing more than 16 per cent silicon, the cooling curves are similar to those containing no carbon. Alloys containing more than 16 per cent silicon show a transformation at about 90°C., due to free silicide. For further details, Honda's original work should be consulted.[6]

Between room temperature and the A_2 point, several other magnetic transformation points have been reported, but they are very weak and the existence of most of them is in doubt. As the Ac_2 point is approached (see Fig. 88*), the permeability increases rapidly for weak magnetizing forces with a sharp decrease as the decalescence point is reached, the permeability above the Ac_2 point being a little greater than one. Some typical results,[3] are given in Fig. 122. For large magnetizing forces, this increase in permeability does not occur, but there is a decrease, the rate becoming large as the decalescence point is approached. In general, increasing temperature causes a decrease in the saturation value of iron and steel. This accounts for the effects at large magnetizing forces. At the same time, increasing temperature apparently tends to weaken the bonds holding the elementary magnetic elements in position, thus allowing them to turn more easily under the influence of an external magnetic field. Thus, with a weak field, which does not carry the iron near saturation, increasing temperature improves the magnetic properties until the Ac_2 point is nearly reached. As mentioned in the previous chapter, this A_2 point is approxi-

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* Chap. IX.

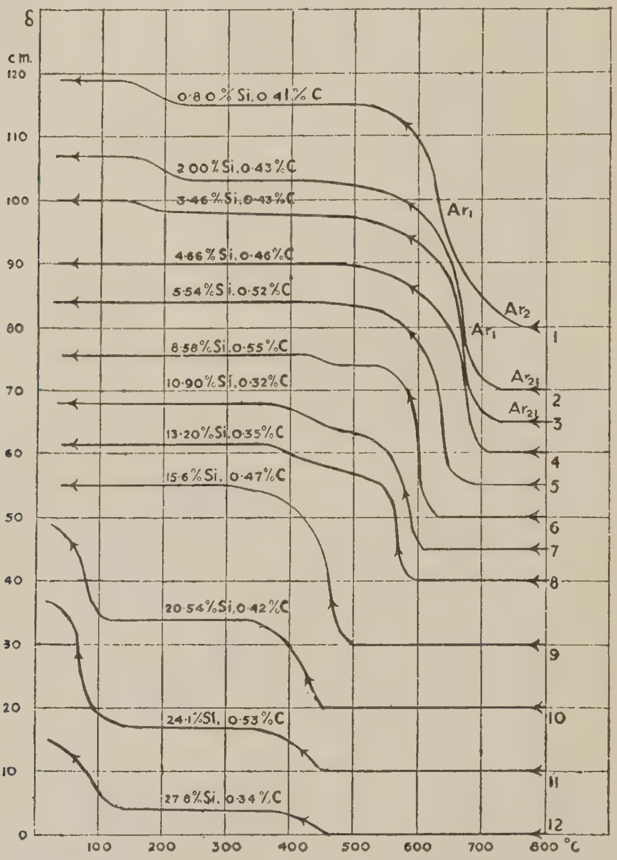

FIG. 121.—Magnetic transformation of a 0.4 per cent carbon steel cooled from 900°C.

δ is proportional to the induction.

mately the same for increasing and decreasing temperatures, and is very little effected by carbon content. It occurs at about 768°C. If sufficient care is taken in the measurements, the magnetic and thermal A_2 points will be found to occur at practically the same point. Figure 93 shows that silicon considerably lowers the A_2 point. Other alloying elements, as will be mentioned later, have an even greater effect.

As mentioned previously and as shown by Fig. 95, there are definite magnetic changes at the A_3 and A_4 points, with a gradual change before reaching and after these points are passed. These magnetic effects are so weak, however, that they are classed as paramagnetic rather than ferromagnetic. The magnetic transformation points may be determined approximately from any reliable equilibrium diagram for the iron-carbon series, provided any other alloying elements which may be present are taken into account.

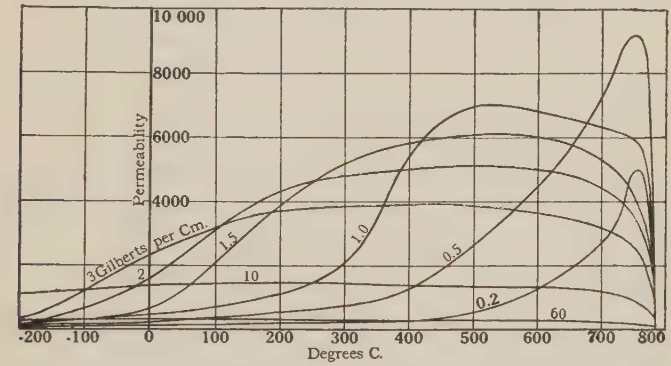

FIG. 122.—Variation of permeability with temperature at different magnetizing forces for electrolytic iron annealed at 800°C.

Some interesting data on the effect of temperature on the magnetic properties of electrolytic iron are given by Terry.[3] Figure 123 gives some typical magnetization curves for an annealed sample, and Fig. 122 gives the corresponding permeability curves. The very high permeability for small magnetizing forces just before the magnetic transformation is reached should be especially noted. Figure 124 gives data on the hysteresis losses. These results are typical for low-carbon iron, although the specific values will vary over a wide range for various samples, depending on the heat-treatment, etc. For electrolytic iron the curves are also affected by the hydrogen content.

MacLaren[7] has given somewhat similar data on commercial electrical sheet. His results were obtained ballistically. Figure 125 shows some characteristic loops for 0.693-millimeter low-silicon steel. The corresponding hysteresis losses, plotted against temperature, are given in Fig. 126. It will be noted from the time curve that there were several pauses in the heating curve. At the pause just under 200°C., there was a corresponding increase in loss. This was due to aging. From the loops of Fig. 125 it will be seen that the permeability corresponding to about 10 kilogausses increased with increasing temperature up to about 260°, and then decreased to about its original value at 502°, and continued to decrease until it became nearly one at the magnetic transformation point.

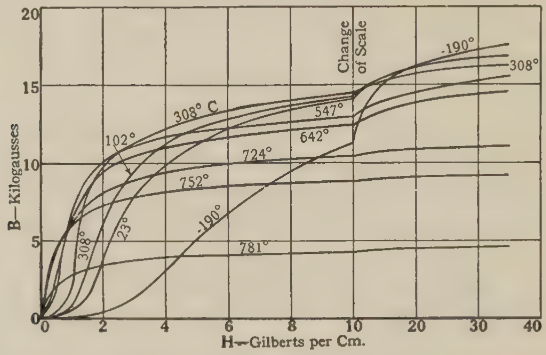

Fig. 123.—Normal induction for various temperatures of electrolytic iron annealed at 800°C.

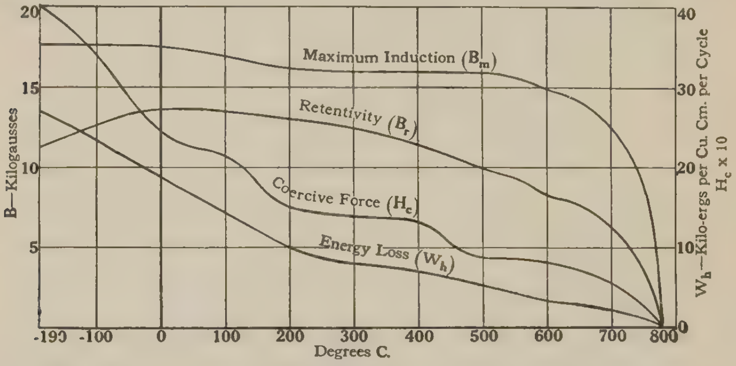

Fig. 124.—Variation of hysteresis constants with temperature of electrolytic iron annealed at 800°C.

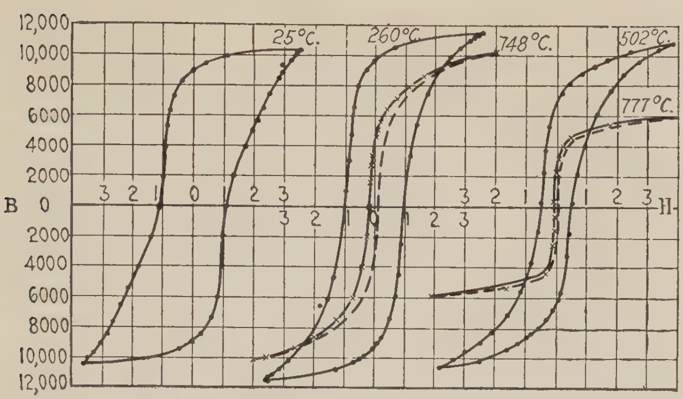

FIG. 125.—Hysteresis loops for 0.693-millimeter low-silicon steel.

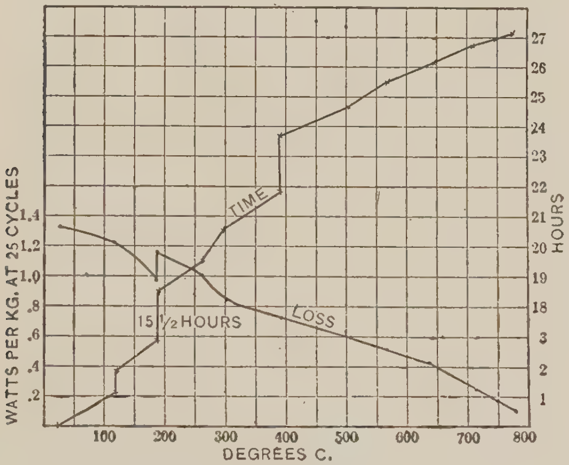

FIG. 126.—Losses for 0.693-millimeter low-silicon steel.

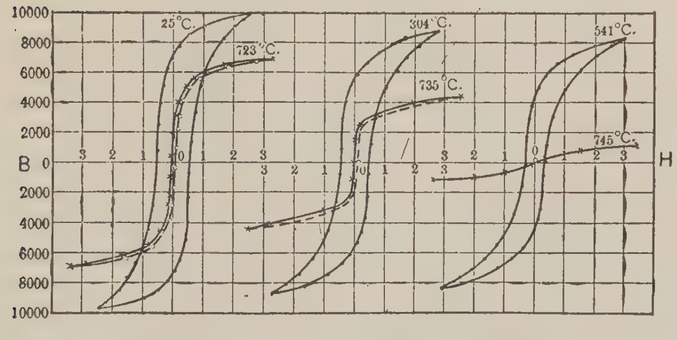

FIG. 127.—Hysteresis loops for 0.348-millimeter high-silicon steel.

Some hysteresis loops for a sample of high-silicon transformer steel having a thickness of 0.348 millimeter are given in Fig. 127, and Fig. 128 shows the corresponding hysteresis loss plotted against temperature. From the hysteresis loops, it will be seen that for this material there was no rise in permeability with increasing temperature at an induction of 10 kilogausses, but the permeability gradually fell from the beginning. For this sample, it was found that the permeability became practically unity at 750°C. for rising temperature, and began to increase again at 740°C. for a falling temperature. Except at this point, the heating and cooling curves practically coincide with respect to the magnetic properties.

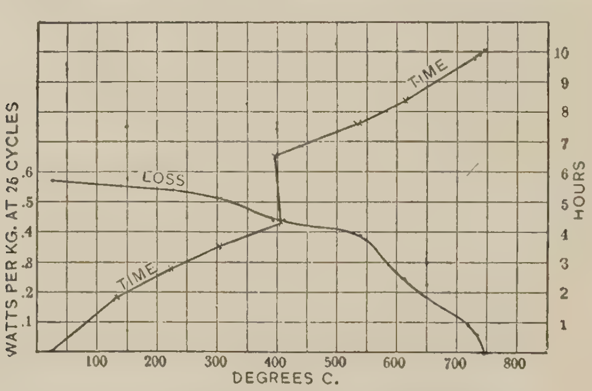

Fig. 128.—Losses for 0.348-millimeter high-silicon steel.

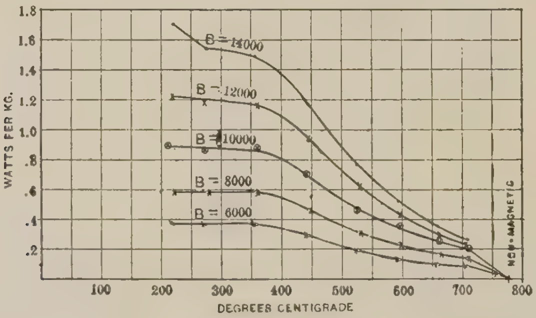

Fig. 129.—60-cycle hysteresis loss as a function of temperature for a low-silicon steel.

MacLaren also obtained some interesting data using an a.-c. method.[8] He determined the total loss for two frequencies and various temperatures, and was thus able to separate the hysteresis and eddy-current losses. Figures 129 and 130 give some typical results. Perhaps, the most interesting feature of these tests is the fact that the hysteresis exponent remains about constant at 1.6, regardless of the temperature, even though the results are taken very close to the transformation point and the specific hysteresis has been greatly decreased. The eddy-current loss values are not very consistent, but this may be due to experimental errors, since it is difficult to separate the hysteresis and eddy-current factors accurately, especially when the latter are small. It would be expected that, due to the increase in resistance due to increase of temperature, the eddy losses would decrease considerably with temperature. The fact that apparently they do not in the case of silicon steel must be laid either to experimental errors or to some complicated change in flux distribution due to the variations with temperature of the permeability in the grain-boundary material. If it should happen that the boundary material decreased in permeability, with temperature increase, at a faster rate than the rest of the steel, the observed results might easily be obtained.

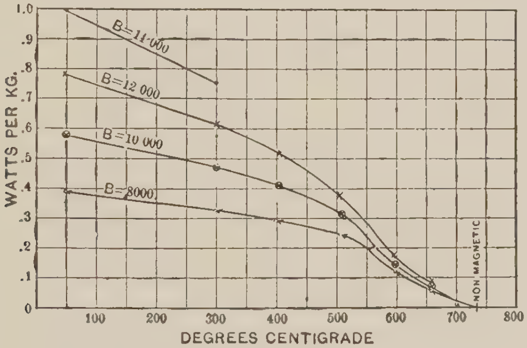

FIG. 130.—60-cycle hysteresis loss as a function of temperature for a high-silicon steel.

Nickel undergoes a magnetic transformation from ferromagnetic to paramagnetic properties, as does iron, but at a much lower temperature. The completion of this change, according to Honda, occurs at 380°C. Apparently, nickel undergoes no allotropic change with increasing temperature, as does iron, and so the magnetic properties change gradually, thus corresponding to the A_2 transformation for iron. A typical curve is shown in Fig. 131.

Cobalt has a magnetic transformation with temperature similar to that of nickel, in that it is somewhat gradual, but its temperature is considerably higher than that of iron. The completion of this change, according to Honda, occurs at 1150°C. A typical curve is shown in Fig. 131.

Iron-nickel Alloys.—The magnetic transformation characteristics of nickel-iron alloys with temperature are quite different for low percentages of nickel than for high. The discontinuity occurs at about 30 per cent nickel (see Fig. 115*), which is the point at which the atomic structure changes from the body-centered cubic to the face-centered cubic, as mentioned in the previous chapter. It will be noted that, for a 30 per cent alloy, the material may or may not be magnetic, depending on its previous thermal history. For alloys having less than 30 per cent of nickel, there is a considerable range of temperature over which the steel may exist in either state. For instance on heating a 10 per cent nickel alloy, the material loses its magnetism at about 690°C., but on cooling does not regain it until the temperature has dropped to 400°C. Above 30 per cent nickel, the transformations are reversible, though their temperature values are slightly influenced by the previous thermal history. Figure 114 summarizes these results. The transformation temperatures are considerably influenced by the carbon and manganese contents, as well as by the nickel. Carbon has a much greater effect than manganese. These elements lower the transformation temperatures.†

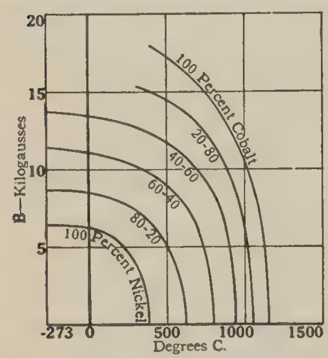

FIG. 131.—Induction-temperature data for nickel-cobalt series corresponding to high magnetizing forces.

Iron-cobalt Alloys.—There seems to be little reliable data available concerning the temperature-magnetic properties of iron-cobalt alloys. Apparently, there is a rather rapid drop in the critical temperature as iron is added to cobalt. By the use of a series of iron-cobalt and iron-nickel alloys, it is possible to obtain a material having any desired magnetic transformation temperature between 1150°C. and room temperature.

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* See Chap. IX.

† For much more complete temperature-magnetic data see Chap. IX, reference **11**.

Iron-manganese Alloys.—The temperature effects for this series, in general, are irreversible, and have been discussed in the previous chapter. Figures 116 and 117 show the nature of these effects.

Iron-silicon Alloys.—The magnetic critical points for this series could be predicted from the constitution diagrams of the previous chapter. The A_2 points as determined thermally are, of course, the ones referred to. In the case of iron-carbon alloys, silicon has a large influence on the various magnetic-thermal transformations. Honda[6] has made a very thorough investigation of these effects as previously mentioned (see Fig. 121). For instance, with high-silicon contents, the A_0 point may disappear, due to the fact that the formation of cementite is prevented by the silicon. In general, it may be stated that the A_2 points are considerable lowered for pure iron-silicon alloys as the silicon increases, but to nowhere near the same extent as for nickel or manganese.

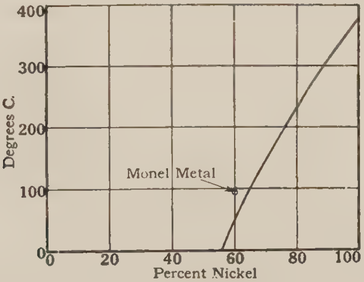

Fig. 132.—Temperature of magnetic change for copper-nickel alloys.

Nickel-cobalt Alloys.—The magnetic-temperature effects for this series are summarized in Fig. 131 as reported by McKeehan,[9] but originally due to Bloch. The critical points and the saturation values both increase as the percentage of cobalt increases.

Nickel-copper Alloys.—The critical points for this series are shown in Fig. 132. The results were obtained from several sources and may be slightly in error. Monel metal, which for the sample considered consisted of 60 per cent nickel, 33 per cent copper, and 6 per cent iron, loses its magnetism at 95°C., according to Burrows.[10] The presence of the iron makes this point fail to coincide with the curve.

Heusler Alloys.—Since these alloys are so variable in composition and so sensitive to thermal effects which produce irreversible magnetic changes, it is hardly worthwhile to consider the reversible effects for any given alloy under specific conditions, unless there is some definite application for the information.

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CHAPTER XI

ALTERNATING MAGNETIZING CURRENT

In order to make the discussion as clear as possible, the specific case of a closed magnetic circuit, such as a ring of laminated material, may be considered, surrounded by a uniformly spaced winding having negligible resistance; and a sine wave of voltage applied to this winding is assumed. Due chiefly to the fact that the permeability of iron varies with the induction, the magnetizing current under these conditions will not have a sine shape, but will contain harmonics. These harmonics will increase, with respect to the fundamental, as the induction increases; namely, the magnetizing current will become more and more distorted as the voltage increases. The presence of hysteresis, moreover, will make this current unsymmetrical to the right and left of the maximum. In order to illustrate exactly what happens, a definite hysteresis loop may be assumed and the magnetization curve plotted from it on the basis of an applied sine-wave voltage which, under previous assumptions, means a sine wave of flux. Figure 133 shows such a construction.

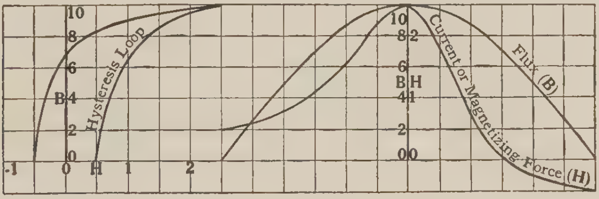

FIG. 133.—Relation between hysteresis loop and magnetizing current.

The ordinates of the current wave are proportional to the abscissæ of the hysteresis loop; namely, at zero flux the ordinate is proportional to the coercive force H_c. The distortion of the exciting current from the sine form is very evident. In the actual case of alternating flux, of course, the current wave would not have quite the form shown, because there would be some eddy-current loss in the steel core which would modify the current.

The eddy loss for ordinary frequencies and thicknesses of laminations adds a component of current approximately in phase with the applied voltage.

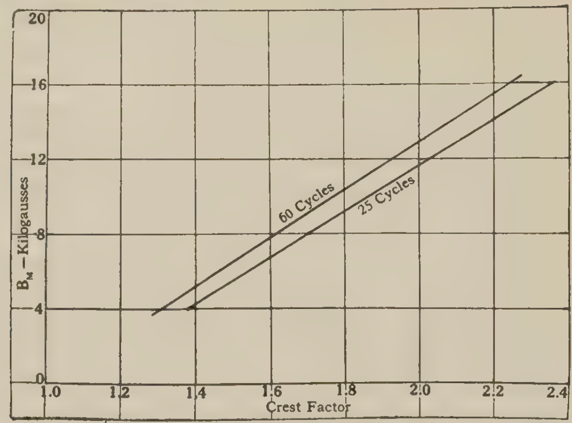

FIG. 134.—Crest factor of exciting current of a power transformer built of silicon-sheet steel.

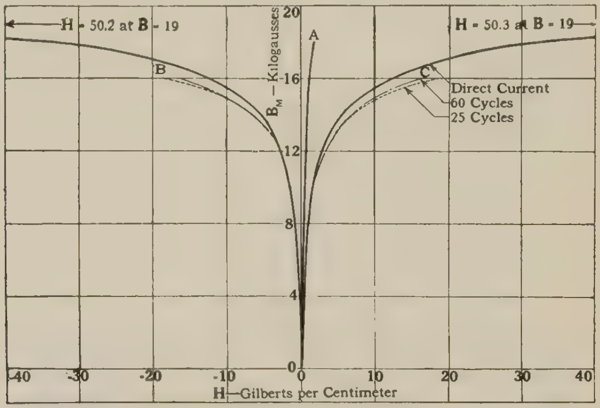

FIG. 135.—Fundamental component of exciting current of a single-phase transformer built of 4 per cent silicon steel.

Data obtained from hysteresis loops and circular oscillograms. In Figs. 135–139 time was assumed to be zero at the crossing in the positive direction of the time axis by the voltage wave. Flux wave was of the sine shape. Induction was computed with the assumption that steel core had a solid section with a specific gravity of 7.5. A = sine component, B = cosine component, and $C = \sqrt{A^2 + B^2}$, or resultant.

If a magnetizing-current wave, as obtained by oscillograph or as plotted from the hysteresis loop as shown by Fig. 133, is analyzed, it will be found to contain a large third harmonic, a smaller fifth, a still smaller seventh, and so on. G. H. Cole in a recent article[1] has brought out these effects very clearly by making a rather complete analysis of a large power transformer having a silicon-steel core.

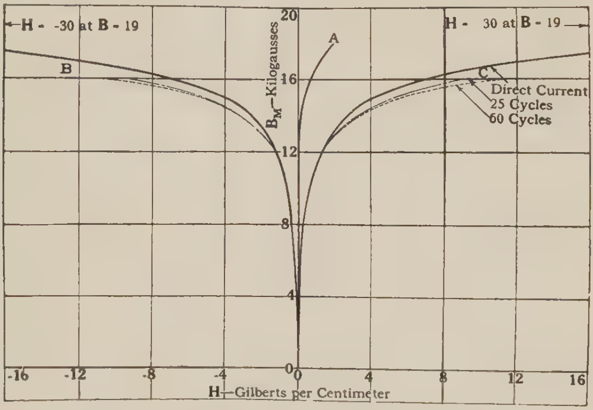

Fig. 136.—Third harmonic of exciting current.

The crest factor (ratio of maximum to root-mean-square current) of the magnetizing current is given by Fig. 134. The crest factor of a sine wave is, of course, the $\sqrt{2}$ or (1.41).

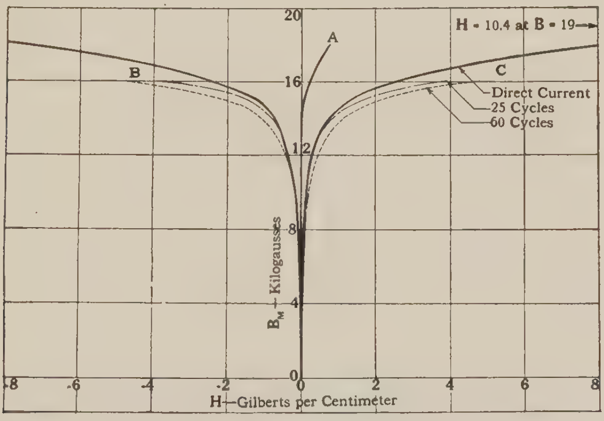

Fig. 137.—Fifth harmonic of exciting current.

The way in which the various components of the exciting current increase with induction is shown in Figs. 135 to 139. The effect of the eddy-currents is illustrated by the results obtained by direct current and by 25 and 60 cycles. The results are summarized by Fig. 140, in which the harmonics are expressed in percentages of the equivalent sine wave; namely, a sine wave of current having the same r.m.s. value as the r.m.s. value of the actual current wave. As Cole points out, if the inductions were carried high enough, it is probable that the harmonic percentages would start to drop as the iron approached a permeability of one for the highest inductions.

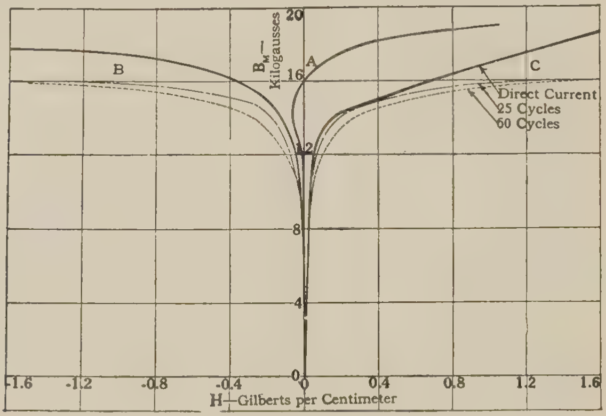

FIG. 138.—Seventh harmonic of exciting current.

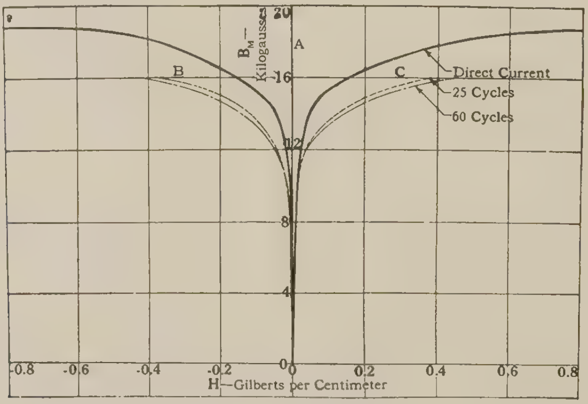

FIG. 139.—Ninth harmonic of exciting current.

Vidmar[2] has given a very good analysis of the effect of these harmonics in the current wave on transformer performance, in which he considers the effect of the third and fifth harmonics only. He obtained his analyses by considering the d.-c. magnetization curve of the material, thus neglecting the comparatively small effect of hysteresis.

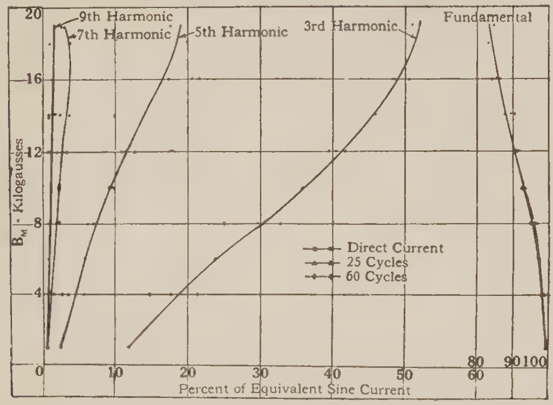

FIG. 140.—Harmonic components of exciting current of a single-phase transformer built of silicon steel.

The third and fifth harmonics, as based on the fundamental for various inductions, are shown in Fig. 141. The percentages are somewhat higher than given by Cole, due chiefly to the fact that Vidmar uses the fundamental component as a standard, while Cole uses the larger equivalent sine-wave value as the basis for comparison. Vidmar shows that if the d.-c. magnetization

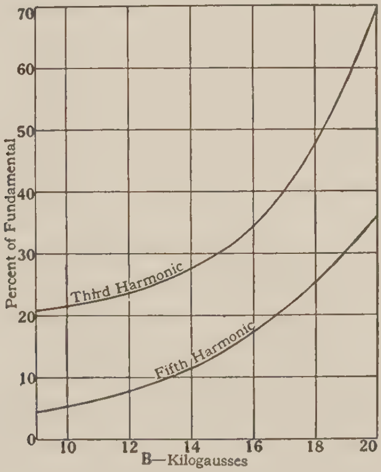

FIG. 141.—Third and fifth harmonics in per cent of fundamental.

curve for a material is taken and the magnetizing current I_m corresponding to the maximum induction is divided by $\sqrt{2}$, calculated values for the exciting current will be obtained which are much higher than the true alternating exciting current for high inductions. This is due to the current distortion. Figure 142, due to Vidmar, shows the amount by which this $I_m\sqrt{2}$ value is in excess of the true r.m.s. value of the exciting current, considering only the third and fifth harmonics in addition to the fundamental. Cole's crest-factor curves of Fig. 134 show similar results, but are expressed somewhat differently.

These harmonics in the exciting current have a number of effects which sometimes are quite important. In addition to making more difficult the calculation of the exciting current from the d.-c. characteristics, they introduce difficulties in testing for core losses. It may be simply mentioned here that the harmonics in the exciting current produce resistance drops in the exciting winding which cause the voltage actually applied to the core (secondary voltage) to be different from a sine wave, although the supply to the primary has that form. As a consequence, the secondary voltage wave is peaked, the flux wave becomes flat, and the result is that, for a given r.m.s. voltage, the core loss in the transformer or sample under test is reduced over what it would be if there were no harmonics in the current wave.

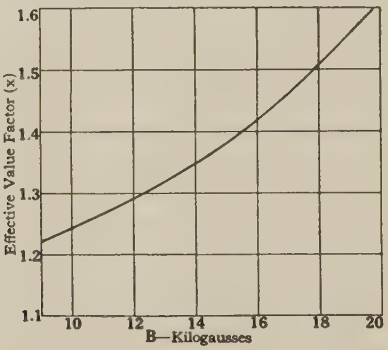

FIG. 142.—Showing ratio of calculated r.m.s. current to true value (based on fundamental, third, and fifth harmonics only).

$$X = \frac{I_m/\sqrt{2}}{I_{rms}},$$

where I_m is the d.-c. magnetizing current corresponding to the maximum induction.

Again, these harmonics, particularly the third, produce many curious and sometimes harmful effects in three-phase transformer systems containing single-phase or polyphase transformers. Large third-harmonic currents or third-harmonic fluxes are set up which may cause abnormal voltages or losses in parts of the system.

If, instead of a sine-wave voltage being applied to a transformer, a sine-wave current is applied to the primary, the flux and therefore the voltage across the transformer will contain harmonics. In general, there are harmonics in both the current and voltage.

Due to the large reluctance of the air-gaps and other portions of the magnetic circuit in rotating machines, these particular harmonics due to the core characteristics are of little importance in such apparatus, but in the case of transformers their effects must be carefully considered. If their fundamental characteristics are understood, the analysis of a specific problem, in general, can be readily made.

References

1. The Magnetic Properties of Silicon Steel in a Large Transformer, G. H. COLE, *The Electric Jour.*, January, 1924.
2. The Transformer Magnetizing Current and its Higher Harmonics, MILAN VIDMAR., *E. u. M.*, June 10, and 17, 1923.

CHAPTER XII

MECHANICAL AND THERMAL PROPERTIES OF ELECTRICAL SHEET

Mechanical Properties.—In general, the mechanical properties of electrical sheet are of minor importance, except in the case of high-silicon alloys. The brittleness of the material is the factor which limits the permissible amount of silicon in commercial sheet; first, because of the difficulty of rolling; and second, on account of the difficulty of punching. If it were not for this brittleness, it would be possible to use considerably higher silicon contents to advantage for certain applications, since the hysteresis and eddy losses would be thus decreased. Yensen has shown that, when very pure materials are used in the preparation of iron-silicon alloys, it is possible to increase the silicon content quite appreciably, over that ordinarily considered the safe commercial limit, without producing undue brittleness. The physical data shown in Table XIX, as obtained from a number of sources, are probably fairly representative.

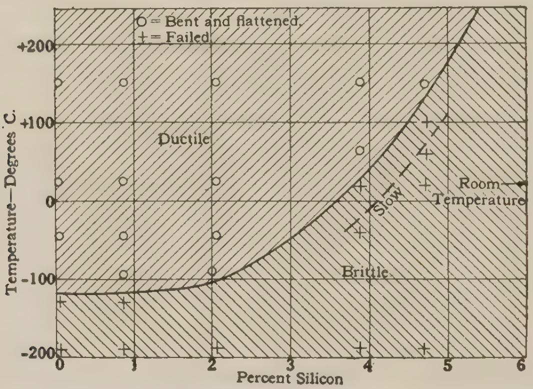

FIG. 143.—Effect of silicon on temperature of incipient ductility of silicon steel.

For silicon contents between these values, the mechanical properties will be intermediate. The above results are for stresses parallel to the direction of sheet rolling. For stresses at right angles to the direction of rolling, the tensile strength and the elastic limit will be, perhaps, 10 per cent higher, and the percentage of elongation will be slightly lower.

Measures of brittleness for sheet material are not as yet very well standardized. G. H. Cole has recently found that the Erichsen test is a very satisfactory one for this purpose when applied to electrical sheet. Erichsen values for high-silicon sheet will average about one-half those for 1 per cent silicon. For Erichsen values below 4, the sheet will be found difficult to punch at ordinary temperatures. As shown by Pilling,[1] Fig. 143, however, by slightly raising the temperature it is often possible satisfactorily to punch material having a considerably lower Erichsen value. It will be found that the brittleness from one sheet to another of a given heat and even from one part to another of the same sheet may vary over wide limits. For this reason, in order that a brittleness test shall be of any value, a considerable number of samples from a given heat must be taken.

TABLE XIX.—PHYSICAL CHARACTERISTICS OF SILICON STEEL

Property	1 per cent silicon	4 per cent silicon
Tensile strength, pounds per square inch	45,000	80,000
Elastic limit, pounds per square inch	25,000	45,000
Per cent elongation	18	3

Due to their hardness, silicon steels are much more severe on the dies than ordinary open-hearth steels. The wear on the dies is greatly accentuated in the case of the high-silicon steels by the heavy scale which is often present, and which has a considerable abrasive action.

As has been previously pointed out, this heavy scale is a disadvantage from a magnetic standpoint, as it increases the hysteresis losses at high inductions. If it is present, it must adhere tightly to the sheet, since otherwise the enamel will peel off, taking the loose scale with it. This adherence can be accomplished only by proper mill practice. In Germany it is common in the case of high-silicon sheet to remove the scale by pickling. This usually leaves a rough sheet with a very poor space factor. If the scale is to be removed, it probably should be done before the final rolling.

Thermal Conductivity.—Much of the heat which is generated in the cores and windings of electrical apparatus is conducted to the surface through the laminations. Thus, it is of considerable importance to know the thermal conductivity of electrical sheet in order to calculate the probable temperature rise in any specific structure. It is obvious that the conductivity parallel to the laminations is much higher than at right angles, and therefore most of the heat is dissipated in the direction of the laminations.

The thermal conductivity of electrical sheet is given in Table XX. These are average results as obtained by a number of observers. The longitudinal conductivity is little affected by pressure, but the transverse conductivity varies with pressure and with the nature of the enamel or other insulating material between the sheets. The effect of pressure on conductivity as reported by Taylor[2] is given in Table XXI.

TABLE XX.—CONDUCTIVITY OF SILICON STEEL

Material	Longitudinal	Transverse
Low silicon....	1.2 watts per inch per degree centigrade	0.014 watts per inch per degree centigrade
High silicon...	0.5 watts per inch per degree centigrade	0.013 watts per inch per degree centigrade

TABLE XXI.—TRANSVERSE CONDUCTIVITY IN WATTS PER INCH CUBE PER DEGREE CENTIGRADE

Material	Temperature, degrees centigrade	Conductivity	Pressure, pounds per square inch
0.0172 in. low silicon....................	99	0.0106	0.81
0.0172 in. low silicon....................	86	0.0212	25.7
0.0172 in. low silicon....................	83	0.0234	54.1
0.0172 in. low silicon....................	91	0.0265	85.7
0.0172 in. low silicon....................	91	0.0295	125.0
0.014 in. high silicon....................	77	0.0093	0.82
0.014 in. high silicon....................	70	0.0133	15.0
0.014 in. high silicon....................	81	0.0154	32.7
0.014 in. high silicon....................	88	0.0156	46.7
0.014 in. high silicon....................	81	0.0163	61.0
0.014 in. high silicon....................	80	0.0174	101.0
0.014 in. high silicon....................	77	0.0182	131.0

Transformer-core pressures are usually 20 pounds or less, while pressures in rotating machines will correspond more nearly with the highest pressures given in Table XXI. It may be seen that little heat can pass across the laminations unless the temperature gradients are very high. The lower longitudinal thermal conductivities of the high-silicon material as compared with the low-silicon steel could be anticipated, because low thermal conductivity and low electrical conductivity usually go hand in hand.

References

1. Low-temperature Brittleness in Silicon Steel, N B. Pilling, *Trans. A.I.M.E.*, Feb., 1923.

2. Thermal Conductivity of Insulating and other Materials, T. S. Taylor, *The Electric Jour.*, vol. 16, p. 526, Dec., 1919; also *Jour. A.S.M.E.*, vol. 42, p. 8, Jan. 1920.

PART II

MAGNETIC TESTING

CHAPTER XIII

INTRODUCTORY AND THE VALUE OF COMMERCIAL MAGNETIC TESTING

INTRODUCTION

In the following chapters of this portion of the book the various principles involved in magnetic testing will be described, and then illustrated by specific examples; finally, the suitability of the various methods for research work and for commercial testing will be pointed out, as determined by the material to be tested, the accuracy desired, and the speed which is necessary. For research work, where accurate fundamental data are sought, it is justifiable to use laborious methods and complicated apparatus. When routine acceptance tests are to be made on many samples a day, accuracy may be sacrificed for speed, reproducibility of results being the only essential.

A mere description of various types of testing apparatus as found in the usual textbooks and handbooks, while of value to the expert, may be of little use to the novice, since he is unable to judge of the value, suitability, and limitations of any particular apparatus or method for the purpose which he has in mind. The attempt, here, is to supply that deficiency which is common to most published data on magnetic testing. It is realized, of course, that there is danger of being unfair to certain types of apparatus, due to lack of personal experience. Whatever recommendations are made, then, may be biased, but effort will be made to make them as impartial as possible.

An approximate determination of the magnetic properties of materials is relatively simple. There are many methods available, however, and many kinds of magnetic materials. The method to use should be determined by the purpose for which the tests are being made, the kind of material to be tested, the amount of testing to be done, and the speed and accuracy desired. No one method at present available is most suitable for all purposes.

THE VALUE OF COMMERCIAL MAGNETIC TESTING

The value of magnetic measurements is obvious when used in research work involving the development of new or improved magnetic materials. Often, however, the full value of magnetic testing is not completely realized when considered in connection with routine inspection. It is the purpose here to point out not only the more or less obvious uses of such inspection, but some which are not so obvious. That commercial testing is of considerable value is shown by the fact that most steel companies manufacturing material for magnetic purposes and most large users of these materials have well-equipped magnetic laboratories for routine inspection. By far the most important type of magnetic material, both on a basis of tonnage and value of annual output, is electrical sheet; that is, the material which is used for the cores of electrical apparatus.

Commercial Test Methods.—The actual methods of measurement will not be described in detail in this chapter, but will be considered only very briefly here. The most common and the most valuable magnetic test for sheet material is perhaps the Epstein test in one of its various forms.* This test is simply a method of determining the total hysteresis and eddy losses in electrical sheet for a given alternating flux of a given frequency. The standard test is made at a maximum induction of 10 kilogausses (and sometimes 15 kilogausses). If desired, the hysteresis and eddy losses can be separated by any one of a number of methods. The combined hysteresis and eddy loss is designated as $W10/60$ for a maximum induction of 10 kilogausses and a frequency of 60 cycles.

Some manufacturers consider the core loss or Epstein test sufficient, but concerns making high-grade steel for electrical apparatus find that some sort of permeability test is also quite essential. For routine work, this d.-c. test consists of measuring the induction B for certain definite values of magnetizing force H, or the magnetizing force for certain definite values of induction. The ratio $\frac{B}{H}$ $(= \mu)$ is the permeability.

A characteristic normal magnetization curve and the derived permeability curve are shown in Fig. 2, p. 7. It will be seen that small changes in the magnetizing force H produce large changes in induction B for small magnetizing forces, but for high magnetizing forces the change in B for a given change in H is small. The maximum permeability is at a, the point of tangency of a straight line drawn from the origin to the magnetization curve.

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* See Chap. XXII.

There are many types of commercial permeameters available, but one should be chosen which is fairly simple to operate and which gives reproducible results. In order to aid in intercomparisons between various laboratories and, in case of dispute, between the manufacturer and purchaser, it is quite desirable for the permeameter to give results in absolute values and not merely comparative empirical values. If a permeameter is too simple, it may be looked upon with some suspicion; for, probably, a correction factor is required to give true permeability values, and this factor will vary with different materials and different dimensions of the test samples. A few permeameters are available which meet the above requirements sufficiently well for commercial testing.

Significance of Test Values.—Most electrical sheet material is prepared in open-hearth furnaces. The better grades contain various proportions of silicon up to about 4.5 per cent. For a satisfactory material, first, the chemical composition must be correct. As an indication of the sensitivity of the magnetic properties to certain alloying elements, it may be mentioned that even a few thousandths of 1 per cent increase in carbon content* of otherwise pure iron or silicon steel may greatly increase the hysteresis loss and lower the maximum permeability. Other elements do not have so large an effect, but some of them are important. A loss test or a permeability test at moderate inductions is then a useful means of indicating the amount of impurities in a heat of electrical steel. The high-induction permeability, other things being equal, is a function of the silicon content—the greater the silicon the lower the permeability. This is not, however, a very reliable test, since there are so many other disturbing influences. The electrical resistance is a better indication of the silicon content.

Practically all electrical sheet is annealed before being used, since annealing greatly lowers the hysteresis loss and increases the permeability at low and moderate inductions. Even with the best annealing practice, however, there is a great variation in the effect of this process upon the magnetic properties of the steel due to the following factors which are usually subject to the human element:

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* See Chap. IV.

1. Incorrect temperature cycle:
    - *a.* Maximum temperature too low or too high.
    - *b.* Nonuniform temperature in furnace.
    - *c.* Rate of cooling over certain regions of the temperature cycle too fast.
2. Oxidation due to:
    - *a.* Too high temperature.
    - *b.* Boxes or covers not properly sealed from the air.
    - *c.* Too small a charge for the size of the box or cover.
3. Contamination due to presence of carbon or carbon-containing materials which may introduce carbon into the steel.

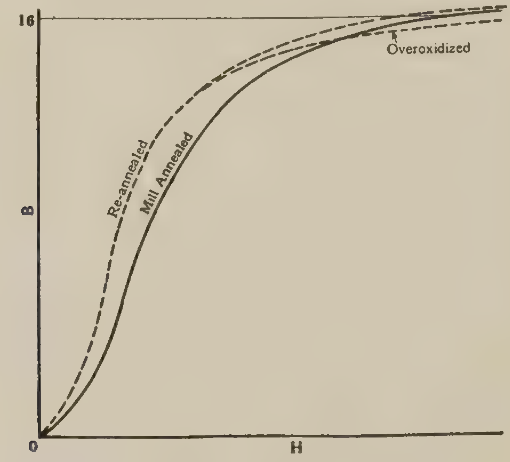

FIG. 144.—Effect of annealing and oxidation.

Frequent routine magnetic inspection is of the greatest value as a check on the annealing processes. For high-grade material, the sheet is usually annealed at the mill and is then re-annealed by the electrical manufacturer after the punching or shearing operation. This second anneal removes the punching strains* and thus improves the magnetic quality. Also, even though there are no punching strains, a double anneal gives better magnetic quality, in general, than a single anneal, as shown in Fig. 144. Both the electrical sheet manufacturer and the user, therefore, need a check on the annealing process.

* See Chap. VIII.

Magnetic tests which indicate faulty annealing will be considered in detail.

1. *a*. If the maximum temperature is too low, the Epstein or loss test will be high and the maximum permeability will be low. For electrical sheet, the maximum permeability occurs in general at inductions between 6 and 10 kilogausses. A test, therefore, for magnetizing force H for a definite induction in this range will be satisfactory. In order to indicate the sensitivity of this test, it may be stated that a correct anneal will decrease the total loss 50 per cent or more from the value "as rolled," and will increase the maximum permeability several hundred per cent. A suitable re-annealing after shearing, for a sample 1 inch wide, will often increase the maximum permeability 100 per cent.

If the temperature is too high, there is generally the effect of 2—*a*, namely, overoxidation. This is most readily made manifest by a high-induction permeability test, say at $B = 16$ kilogausses. It is not uncommon, in the case of poor annealing, for this permeability to be decreased 25 or even 50 per cent, due to this cause. This means, of course, a comparatively small change in induction for a given H (see Fig. 144), since the magnetization curve is so flat at these inductions. In fact, a 1 per cent decrease in effective cross-section of the sample due to removing active iron by oxidation will mean an increase in H of perhaps 15 per cent for an induction of 16 kilogausses. To apply this test, it is best to have samples of standard material of which the high-induction permeability is known. This change in high-induction permeability produced in samples introduced into the furnace, is a good indication of the nature of the annealing.

1. *b*. If nonuniformity of temperature in the furnace is suspected, this may be checked by placing samples of the same material in different parts. The watt loss or the maximum permeability will give a very sensitive indication of the temperature variations. This is often much easier than introducing thermocouples.

1. *c*. For ordinary commercial electrical sheet and large furnace charges, there is little danger of too rapid cooling unless certain portions of the material are exposed to the air at fairly high temperatures. For small experimental furnace charges withdrawn too soon from the furnace, the rate of cooling may be too rapid for the best results. This condition may be determined by a magnetic test. In the case of certain special alloys, such as

permalloy, the rate of cooling is very critical. A magnetic test is invaluable as an indication of the rate of cooling.

2. *a, b, c.* These are all oxidation effects and are best shown by a test for permeability at high inductions (16 kilogausses or more). A reduction in permeability indicates excessive oxidation. If the magnetic test indicates such low permeability and the composition of the materials is right, it is usually easy to determine whether or not the cause is *a, b, c,* or a combination.

3. If the material has been contaminated by carbon, the losses usually will be high and the maximum permeability low. The high-induction permeability will not be appreciably affected.

In addition to chemical composition and annealing, another factor which must be considered is space factor, as affected by rough sheets or scale. Obviously, if there is such a condition, less active steel can be inserted in a given space and the net result is high magnetizing force for a given total flux. Since the ordinary magnetic tests are made on the basis of a given weight of material, and the cross-section is calculated from that and an assumed specific gravity, the loss test will not indicate this unsatisfactory condition. A permeability test at high inductions, however, will indicate rough or pitted sheets, or excessive scale.

The desirability of high permeability at high inductions should be obvious. Reference to Figs. 2 and 144 shows that a small change in the induction caused by chemical composition, oxidation, or rough sheets makes a very large change in magnetizing force as saturation is approached. In transformers, the magnetizing current becomes appreciable with reference to the load current, which means very low power factor on light loads, and in the case of the teeth of rotating machines the tooth reluctance becomes comparable with that of the air-gap, thus giving a low power factor and reduced torque for a.-c. machines, or reduced torque for d.-c. machines. High-induction permeability is thus often more important than reduced losses.

Commercial Application of Magnetic Testing.—It is evident, then, that the sheet manufacturer can use routine magnetic tests to great advantage in order to be enabled to make a uniform product, since it gives him a check on (1) chemical composition, (2) heat treatment, (3) condition of surface of sheet. Also, it enables him to isolate the defective material, thus saving the cost of shipping to the customer and subsequent return; and also it enables him to select superior material for which he can obtain a higher price. At least one large manufacturer of electrical sheet in this country has for many years regularly made such a selection of extra high-grade material and put it on the market as a special grade.

The manufacturer of electrical apparatus often buys this electrical sheet on a magnetic specification—the lower the losses and the higher the permeability, the greater the price. A certain grade of material has definite upper and lower limits for loss, and a limit or limits for permeability below which the material must not fall. In order that the customer shall be sure that he is getting what he is paying for, it is essential that he make routine magnetic tests. Even though the electrical sheet manufacturer is reliable, it may happen that heats of steel become mixed or are incorrectly stenciled. If this happens, suitable magnetic testing will indicate the difference before the material has been punched and assembled in the completed apparatus, thus saving much expense, as otherwise machines might have to be torn down and new iron supplied. In these days of high-efficiency transformers, with loss and exciting-current guarantees, it is absolutely essential to use the correct core material.

It sometimes happens that a customer for electrical apparatus will offer a bonus for low loss or low exciting current. If the electrical manufacturer has accurate test results covering his available stock of electrical sheet, he can select his core material so that he can obtain a maximum bonus. This one thing may pay for the cost of testing several times over.

In the case of laminated material for poles, a high-induction permeability test is quite desirable. This material is frequently subjected to large centrifugal strains (for revolving field machines), and the tensile strength is often specified. It is easy to obtain the required tensile strength by the introduction of carbon, but this lowers the permeability. For this reason, the permeability should be checked frequently.

Permanent-magnet Steels.—Aside from electrical sheet, routine magnetic testing is applied largely to permanent-magnet material. Tests for retentivity B_r and coercive force H_c, Fig. 8, for a given maximum magnetizing force H_m or maximum induction B_m are desired. A knowledge of the maximum product of B and H for the demagnetization curve is also desirable.

It is often possible, of course, to form samples of material into magnets, then heat-treat and test in some special type of tester suited to the particular shape of magnet. The manufacturer of magnet steel, however, should know the magnetic properties of his material in terms of absolute units, and these can be best obtained on straight bars tested in a simple permeameter. If a sample does not come up to specification, the steel manufacturer can immediately check his chemical analysis and mill practice, and determine the cause of the difficulty before making a large tonnage of inferior material.

The customer will find routine magnetic tests of great advantage as a check on the quality of the material as received from the manufacturer (the samples of course, must be heat-treated before testing), and as a check on his own heat-treating practice. If the steel manufacturer and the customer both makes tests in absolute units instead of by some empirical method, the various manufacturers and customers can much more readily come to a common agreement, and in the case of dispute can easily submit their samples to an impartial third party, such as the Bureau of Standards. A knowledge of the product being used in terms of standard magnetic units also offers an advantage in considering published data on new materials which appear from time to time. A direct comparison then can be made without the use of conversion factors, which may be quite uncertain.

Other Nonlaminated Materials.—The permeability of frame material for rotating machines is not so important, in general, as for the laminated steel, since the inductions are usually lower in the former case. In some designs, however, the inductions are quite high in the frames, and permeability checks from time to time are desirable. In the case of shunt motors, variations in frame material may cause difficulties in connection with speed adjustment, even though the inductions are not particularly high. Cast coupons are not usually satisfactory, due to the fact that they cool much more rapidly than the frame material. Samples, therefore, should be cut from the frame itself. Samples suitable for a commercial permeameter will often involve the destruction of the frame. Sometimes, however, small ring samples can be obtained without injury to the frame.

In the case of cores for sensitive relays, such as are used in telephone, telegraph, and railway signal work, it is essential to have the apparent residual induction as low as possible. This usually means that the coercive force should be very small. If silicon-steel cores are used, they require about the same chemical composition and heat-treatment as high-grade electrical sheet. A low-induction permeability test makes a very suitable inspection test for material for these applications.

Due to the well-known fact that there is a definite relation between the magnetic and other physical properties of materials, it is often possible to make a simple magnetic test which will indicate from a mechanical standpoint the suitability of a material for a particular application. Such a type of test is known as *magnetic analysis*. Such tests sometimes may be used to indicate chemical composition, previous heat-treatment, and a number of other factors. As the art of magnetic analysis progresses, routine magnetic permeability and loss tests should become more and more important.*

Summary.—Routine magnetic inspection is very useful to the manufacturer of steel and to the manufacturer of electrical apparatus. It gives the steel manufacturer a ready check on the uniformity of his mill processes, chemical composition, and heat-treatment, and enables him to select his material in such a way that he can supply an exacting customer with superior material at an advanced price, and can avoid antagonizing this same customer by giving him inferior material. It is of advantage to the customer in that he can purchase on a definite specification and can assure himself that he is getting what he pays for. It gives him the opportunity of grading his available stock of material so that it can be used to the best advantage; and, finally, it gives him a reliable and sensitive check on the quality of his heat-treatment. The small investment required for simple, accurate, and reliable magnetic-testing equipment will be repaid many times over when used in connection with routine inspection.

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* For a resume of the present state of the art, see the article, The Present Status of Magnetic Analysis, by R. L. SANFORD, *Trans. A.S.S.T.*, June, 1924.

CHAPTER XIV

DIRECT-CURRENT TEST METHODS—GENERAL

The various magnetic properties which it may be desired to measure have been described in previous chapters, particularly in Chaps. II and III. By d.-c. test methods, all of the important magnetic properties except eddy-current losses and the effect of eddy-currents on hysteresis losses as the result of skin effect may be measured if desired. For solid material d.-c. methods are usually essential for determining the fundamental characteristics since the disturbing effects of eddy-currents may be very great, if an attempt is made to use a. c. For laminated materials, however, a. c. methods are very often to be preferred, due to the fact that they are usually simpler and quicker, and correspond more nearly to the conditions of actual use.

In the case of d.-c. methods, two quantities must be measured, namely, the effective magnetizing force and the resulting induction in the specimen. There is, in general, no difficulty in measuring induction with considerable accuracy. It is in a few types of magnetic circuit only, however, that the magnetizing force can be measured readily with any reasonable degree of accuracy.

Methods of Measuring Induction.—These may be divided into the following classes:

1. Magnetometric.
2. Rotating ellipsoid.
3. Magnetic balance.
4. Traction.
5. Deflecting coil.
6. Rotating coil.
7. Bismuth spiral.
8. Polarized light.
9. Ballistic or fluxmeter.
10. Volt-second meter.

1. The *magnetometric* is one of the classical methods used for much of the early magnetic work. If a long sample of magnetic

material is magnetized longitudinally, magnetic poles are generated which may be caused to act on a compass needle or magnetometer. Knowing the distance of the needle from the sample, the length of the specimen and the value of the magnetic field normally acting on it, the induction in the sample may be calculated from the resulting deflection of the needle.

2. The *rotating ellipsoid* method of determining induction is based on the fact that, if an ellipsoid of revolution of paramagnetic or ferromagnetic material is placed in a magnetic field, it will tend to rotate until its major axis is parallel with the field. If the material is diamagnetic, the major axis will tend to place itself at right angles to the direction of the magnetic lines of force. The amount of torque is a measure of the induction in the specimen.

3. If a specimen of paramagnetic material is placed in a nonuniform magnetic field, it will tend to be drawn into the most intense portion of the field. If the material is diamagnetic it will tend to be ejected from the field. The force is proportional to the susceptibility of the material.

4. The *traction* method of measuring induction is based on the fact that the magnetic pull between two pieces of magnetized material is proportional to the square of the induction.

5. The *deflection* of a D'Arsonval meter movement is proportional to the current flowing in its *coil*, and to the strength of the magnetic field in which it moves. If such an element forms a part of a magnetic circuit and the current through the moving coil is kept constant, the deflection of the coil will be proportional to the flux in the magnetic circuit.

6. If a *coil* with its axis at right angles to a magnetic field is caused to *rotate* at a definite speed, a voltage will be generated in it which may be read by means of a suitable voltmeter, and this voltage will be proportional to the flux threading the rotating coil.

7. If a piece of *bismuth* wire coiled up in a convenient form, such as a *spiral*, is placed in a magnetic field, its electrical resistance will change, due to the field, and this change will be a function of the intensity of the magnetic field. By the use of a suitable bridge and calibration for the bismuth, magnetic-field strengths may be readily determined.

8. If a beam of *polarized light* be reflected from a magnetized surface, its angle of polarization will be shifted. The angle of shift is a function of the magnetic intensity at the surface of the

metal, and may be measured in the usual way by means of Nicol prisms.

9. The *ballistic method* is, perhaps, the simplest and most used method for measuring induction. If a magnetized sample is surrounded by a coil of wire connected to a ballistic galvanometer or fluxmeter,* and the flux in the sample is caused to change, or the coil is suddenly removed from the sample, the galvanometer or fluxmeter will be deflected, and this deflection is a measure of the change of flux threading the coil. This same principle is used in connection with certain methods of measuring magnetizing force as well as induction.

10. If a coil of wire surrounds a magnetic circuit, and the magnetic flux is changed, this change of flux is proportional to the $\int e\,dt$, where e is the voltage generated in the coil. If an integrating voltmeter or *volt-second meter* is connected to such a coil, the reading of this meter will be proportional to the change of flux. There is no essential difference between the use of a fluxmeter and a volt-second meter, except that the fluxmeter can rotate only a fraction of a revolution, whereas the volt-second meter can rotate as many revolutions as desired.

Methods of Measuring Magnetizing Forces.—The methods of measuring magnetizing forces are as follows:

a. Long solenoid.

b. Solenoid with ellipsoid sample.

c. Concentric air coils.

d. Magnetic potential coil.

e. Completely closed ferromagnetic circuit with magnetizing coil.

f. Compensation methods.

g. Magnetron.

h. Mercury helix.

a. If a *long*, uniformly wound *solenoid* carries a known current, the magnetizing force at its center will be expressed as follows:

$$H = \frac{0.4\pi NI}{l}; \tag{61}$$

Where H is in gilberts per centimeter or gausses;
N is the total number of turns in the coil;
I is in amperes;
l is the length of the solenoid in centimeters.

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* A ballistic galvanometer differs from an ordinary D'Arsonval galvanometer only in having a long natural period. A fluxmeter is a ballistic

If this solenoid contains an iron sample whose length is several hundred times its diameter, this formula will still hold.

b. If the sample in the above-mentioned solenoid is shorter, the ends will exert an appreciable demagnetizing effect, and the effective magnetizing force will be less than that calculated by formula (61). The method of calculating these demagnetizing factors is given in Chap. V, formula (43), or Fig. 43. The method of applying them is given by formulas (41) and (42). The *ellipsoid* is the only form of bar sample for which the demagnetizing factors can be readily calculated, due to the fact that in such a sample the lines of induction are parallel.

c. If a straight magnetized bar is surrounded by a pair of *concentric* helical *coils* having an equal number of turns, and these coils are connected differentially to a ballistic galvanometer, there is a means of measuring approximately the magnetizing force H by observing the galvanometer deflection when the flux through the bar is reversed. Such a pair of coils may be calibrated by placing them in a long solenoid of known constants with axes parallel, and reversing the current in the solenoid; or the constants may be calculated from the number of turns and dimensions.

d. By means of the Chattock *magnetic potentiometer*[1] (later re-invented by Rogowski and Steinhaus[2]) the magnetic potential between any two points may be measured directly. The method consisted originally in winding uniformly many turns of fine wire on a thin flexible strip of nonconducting material, placing the coil in a known long solenoid, and noting the throw of a ballistic galvanometer connected to the coil when the solenoid current is reversed. Knowing the constants of this coil, or magnetic potentiometer, all that is necessary is to apply its two ends to two points on a magnetic circuit and note the deflection of the ballistic galvanometer connected to the coil. This will give a direct measure of the change of the magnetic potential between the two points, if no magnetic potential is generated by coils or otherwise between the two points.

e. If there is a *completely closed ferromagnetic circuit* surrounded by a uniformly spaced winding, of which the simplest case is the ring, formula (61) may be applied directly to calculate the magnetizing force from the magnetizing current, provided the radial

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galvanometer which has very little restoring torque and which is very much overdamped electromagnetically, *i.e.*, is used in a very low resistance circuit.

width of the ring is several times the diameter.[3] If an air-gap occurs in the magnetic circuit, if there is a change in the cross-section or material, or if the winding is concentrated, the calculation of the magnetizing force then becomes difficult and more or less uncertain.

f. If the reluctance of the joints and the yokes of a magnetic circuit can be *compensated* for, supplying just sufficient magnetomotive force by means of auxiliary magnetizing coils, then formula (61) may be applied directly to the main magnetizing coils for determining H.

g. The *magnetron*, as devised by Hull,[4] may be used for measuring magnetic-field strengths under certain conditions. This device consists of an evacuated glass tube containing a straight filament surrounded by a cylinder. When the filament is heated and voltage is applied between the filament and tube, current passes between the two, due to electronic conduction. Now, if a magnetic field is applied to the tube axially, the electrons will tend to assume circular paths. If the magnetic field is sufficiently strong, the radii of these orbits will become so short that the electrons will not be able to reach the cylinder at all, and therefore no current will flow. If the characteristics of a tube are known, and the voltage is varied until the critical condition is reached, the longitudinal component of the magnetic field may be deduced.

h. If a *helical* channel, filled with *mercury*,[5] surrounds a magnetized bar and carries an electric current, and the ends of the channel are provided with manometer tubes, the mercury will be displaced giving a difference of level in the tubes which will be a function of the current through the mercury, and the longitudinal flux density in the air or H.

1. CHATTOCK, *Phil. Mag.*, vol. 24, p. 94, 1887.

2. ROGOWSKI and STEINHAUS, *Archiv fur Elektrotechnick*, 1, p. 141, 1912.

3. Errors in Magnetic Testing with Ring Specimens, M. G. LLOYD, *Bur. of Standards Bul.*, vol. 5, p. 435, 1908–1909.

4. The Measurement of Magnetic Fields of Medium Strength by Means of a Magnetron, A. W. HULL, *Phys. Rev.*, p. 279, September, 1923.

5. Mercury Apparatus for Measuring Magnetic Fluxes, G. SOMAINI, *Elettrotecnica*, vol. 10, p. 149, Mar. 15, 1923.

CHAPTER XV

DIRECT-CURRENT TEST METHODS—APPLICATIONS

In this chapter the principles outlined in the preceding chapter will be illustrated by specific examples of methods and permeameters which are being or have been used. The particular examples are chosen more for the purpose of illustration than to suggest means for use in magnetic testing. The following chapters will be devoted to a discussion of those d.-c. methods and permeameters which are in most common use.

Magnetometer Method.—This method (1) of measuring induction obviously must make use of methods *a* or *b* (solenoid) for measuring magnetizing force. As described by Ewing in some detail, there are two types of magnetometers—one in which the magnetometer needle is equidistant from the two ends of the sample, and the other in which it is adjacent to one end of the sample. The former is called the two-pole method and the latter the one-pole method.

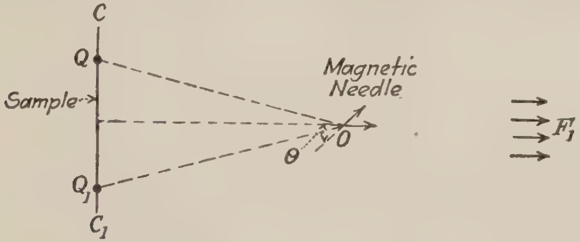

FIG. 145.—Two-pole magnetometer method.

Figure 145 illustrates the two-pole method where CC_1 is the sample in the form of an ellipsoid, and O is the magnetometer needle. In its normal position the needle is in the direction of the horizontal component of the earth's field (F_1), if no other directing force is used. The magnetic poles of the sample are assumed to be concentrated at QQ_1, where $QQ_1 = \frac{2}{3}\ CC_1$. Under these conditions the ferric induction in the bar is:

$$B_f(= 4\pi J) = \frac{3\overline{OQ}^3 F_1 \tan\theta}{a^2 c}, \tag{62}$$

where F_1 is the normal directing force on the magnetometer needle (at right angles to that due to the sample);

θ is the angle of deflection of the needle due to the specimen;

a is the equatorial radius of the sample, in centimeters;

$c = \frac{CC_1}{2}$.

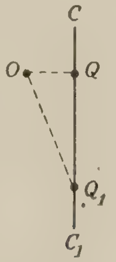

Fig. 146.—One-pole magnetometer method.

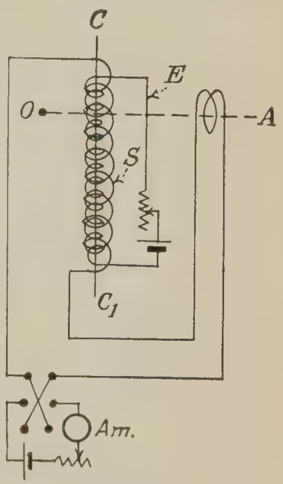

Fig. 147.—Magnetometer with auxiliary apparatus.

The one-pole method is illustrated by Fig. 146. The sample is ordinarily in the vertical position and the needle, at O, is normally directed at right angles to the direction of the paper. If a cylindrical wire, instead of an ellipsoid, is used, the position Q may be found by moving the needle O vertically until the position of maximum deflection is found. Under these conditions the induction is:

$$B_f = \frac{4\overline{OQ}^2 F_1 \tan\theta}{a^2\left\{1 - \left(\frac{OQ}{OQ_1}\right)^3\right\}}. \qquad (63)$$

For the successful use of the magnetometer, certain auxiliary circuits are necessary (see Fig. 147). The magnetizing force is supplied by a uniformly wound solenoid S connected to a battery through a regulating resistance, ammeter and reversing switch. H may be calculated from formula (61) with suitable corrections for the demagnetizing effect of the ends of the sample (see Fig. 43). In series with this circuit is the coil A placed as shown. This is for the purpose of neutralizing the field produced by the magnetizing solenoid S, and is so adjusted that, with the sample CC_1 removed, the magnetometer needle shows no deflection when current flows through S. There is also a second coil surrounding the sample and supplied through the circuit E, the current being so adjusted that the vertical component of the earth's field is just compensated. In order to obtain hysteresis data, additional rheostats and switches are necessary.

Instead of using the earth's field, a directive field may be supplied by a permanent magnetic or other suitable means. In order to determine the field strength, the period of swing of the needle O may be determined in the field F_1. The needle is then removed to a known field, such as that of the earth in a position where there are no disturbing influences, and the period again determined. Then,

$$F_1 = \frac{FT^2}{T_1^2}, \tag{64}$$

where T is the time in seconds for one complete swing in the known field F; and T_1 represents the time in the unknown field F_1.

If desired, a null method may be used which obviates the necessity of knowing the value of the directing field F_1 and the measurement of the angle θ. If a field is supplied from coils placed close to the needle on the axis of the coil A, and the current in the coils is adjusted so that the needle returns to zero, from a knowledge of the dimensions, location, and current in these coils, the induction in the sample may be calculated.

One of the latest types of magnetometers is described by Tyndall.[1] This is an astatic instrument having two needles mounted on a rigid support and separated by a distance equal to the height of the magnetic specimen. One pole acts chiefly on one needle, and the other pole on the other needle. A null method is used. This arrangement overcomes one of the chief objections to the magnetometer method, namely, the effects of disturbances due to varying external fields.

The advantages of the magnetometer method are as follows:

1. It is an absolute method capable of giving correct results from the dimensions and constants of the apparatus.

2. It is capable of following continuous changes in magnetic properties such as those produced by temperature changes.

3. It can be made quite sensitive by using a weak directive force.

The disadvantages are as follows:

1. Except in certain astatic types, it is very susceptible to outside influences, such as trolley lines, movable pieces of iron, or masses of iron subject to temperature changes, etc.

2. Difficulty of obtaining the required samples in the form of long, thin, uniform rods, or of machining shorter samples in the shape of ellipsoids.

3. The complication that, for any but very long samples, the true value of H is a function of B, thus requiring calculations.

In spite of these disadvantages, this method has found considerable use, as much of Ewing's pioneer work was done with it. Recently, in Japan, Honda has used it quite extensively for thermomagnetic investigations, since it is particularly suited to such purposes. It is not used to any extent for commercial testing.

Rotating Ellipsoid.—For intense fields the magnetic properties of a sample having the form of an ellipsoid of revolution may be used as shown by Weiss. If such a sample is suspended in a strong field and rotated until the maximum torque is indicated, which will be at an angle of 45 degrees, the intensity of magnetization J, will be:

$$J = \sqrt{\frac{2T}{V(D_2 - D_1)}}; \tag{65}$$

where T is the torque in dyne-cm.;

V is the volume of the ellipsoid in cm^3.

D_1 and D_2 are the demagnetizing factors corresponding to the major and minor axes (see Chap. V p. 61).

Magnetic Balance.—For the measurement of the susceptibility of paramagnetic or diamagnetic substances, or ferromagnetic materials above the magnetic transformation (Curie) point, some form of magnetic balance, such as that devised by Curie, is particularly suitable. Figure 148 illustrates a form developed by Terry particularly for use in a vacuum and with samples at an elevated temperature.[2] The sample is suspended by an arm in a nonuniform magnetic field shaped about as shown below at the right of the figure. This particular form of field is chosen because it gives a fairly flat force-displacement curve. The force tending to draw the specimen into the field is given by the following formula:

$$F = mXH\frac{dH}{dx}. \tag{66}$$

The force F is in a direction x at right angles to the field H;
m is the mass of the specimen;

X is the susceptibility per unit mass;

$\frac{dH}{dx}$ is the rate of change of flux with displacement at right angles to H.

Instead of determining $\frac{dH}{dx}$, which is rather difficult, F may be measured for a sample of known susceptibility. The F value for an equal weight of the unknown material is then determined, and the relative susceptibilities will be proportional to the forces. In the apparatus of Fig. 148 the forces are measured by means of the two coils *a* and *b* with their axes at right angles. The known substance is placed in the balance, and the current in *a* and *b* adjusted until the maximum torque is obtained. The

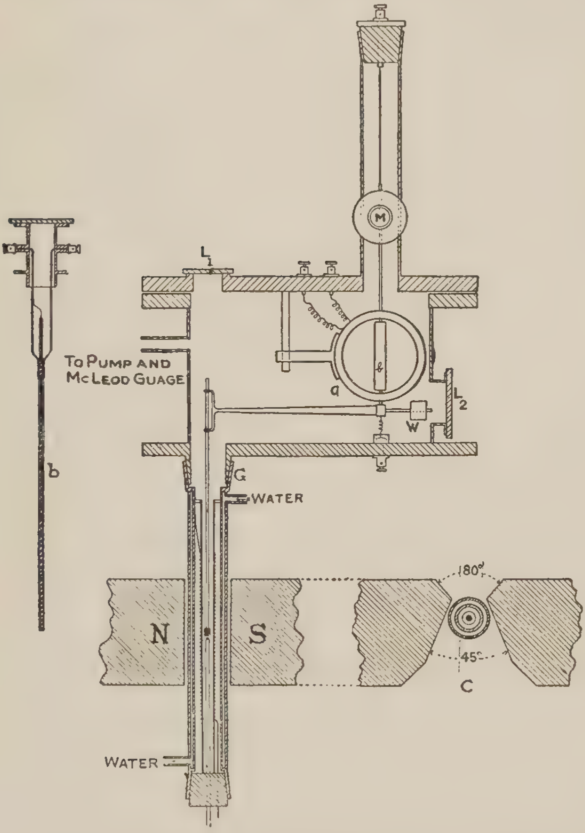

Fig. 148.—Apparatus for measuring the permeability of paramagnetic materials.

position of the spot of light reflected from the mirror M is noted, the unknown material substituted for the known and the spot of light brought back to the same point by altering the current in coils a and b. From the difference in currents, the relative susceptibilities are known.

Traction Methods.—These methods (2) of measuring induction are best exemplified in the Thompson permeameter[3] and the DuBois permeameter.[4] In the former, the induction is measured by noting the pull when the sample is drawn away from the yoke. In the DuBois permeameter, the upper part of the yoke is separated from the lower by two air-gaps and is supported on knife edges. The unbalanced magnetic pull, which is a function of the induction in the sample, is counteracted by sliding weights. The position of these weights, as indicated by a scale, gives the value of B. The magnetizing force is determined from the current in the magnetizing coils which in both permeameters surround the sample. In neither type of apparatus can H be calculated accurately, and it can be determined only by calibrating the apparatus with known samples, standardized by some absolute method. The correction varies with each type of material, and in the Thompson instrument with the condition of the contact surface, friction between the sample and yoke, etc.

A permeameter based on the traction principle[5] also has been devised in which the pull necessary to cause one magnetized piece to slide over another is used as a measure of the induction. This method, of course, is not capable of high accuracy and has not been used to any considerable extent.

These traction methods, of necessity, are subject to large errors and are used very little today, though the Thompson and the DuBois permeameters have been used extensively in the past. They may still find an occasional application when a large number of samples of similar material and of poor permeability are to be compared.

Deflecting Coil.—Method 3, using a deflecting coil for measuring induction, is best illustrated by the well-known Koepsel permeameter, which is similar to a D'Arsonval type of d.-c. meter, with the difference that a constant current is maintained in the moving coil, the permanent magnet is replaced by massive yokes, and the sample to be measured completes the magnetic circuit between the yokes and is surrounded by a magnetizing coil.

This permeameter, which has been used by many experimenters and has yielded much valuable experimental data, has been critically studied by Burrows.[6] Figure 149 shows an outline drawing of the apparatus. The moving coil *h* is supplied from a battery through a milliammeter. This current is maintained constant and of such a value that a pointer attached to *h* reads the induction directly on a uniform scale attached to the instrument. Obviously, in order to make the apparatus read induction directly, this current must be different for each size of specimen. By having suitable sets of bushings *K*, different diameters of sample may be used. The magnetizing coil *S* is so proportioned that:

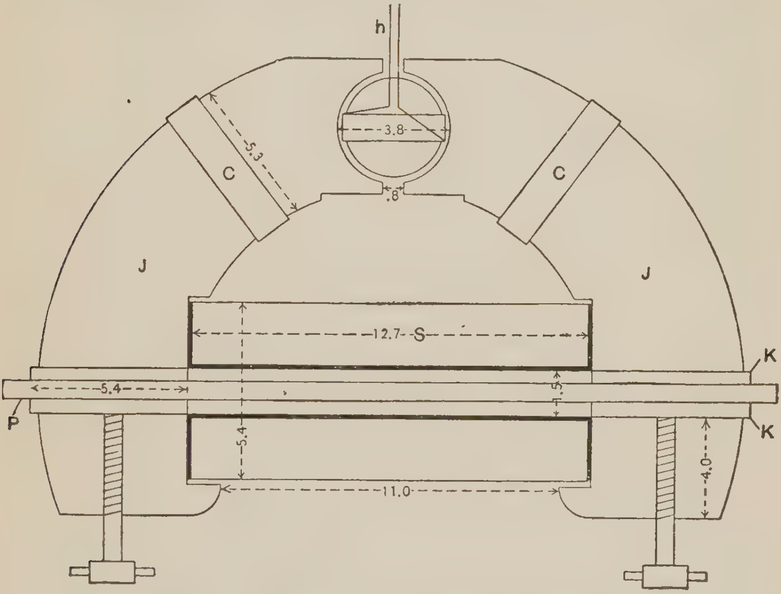

Fig. 149.—Diagram of the Koepsel permeameter.

$$H = 100I.$$

An ammeter in series with this circuit, therefore, reads the magnetizing force directly.

The compensating coils *CC* are connected in series with the magnetizing winding *S*, and oppose the flux due to *S*. They are so adjusted by shunting that *h* shows no deflection when current is applied to *S* and *CC* with no sample in the permeameter.

This instrument is subject to several errors and a number of precautions must be exercised in its use. These have been adequately covered by Burrows. In using this instrument, even after careful demagnetization, it will be found that, when the magnetizing current is reversed, the right and the left deflections of the permeameter, in general, will be quite different, and this difference varies considerably from time to time, even with the same sample. This is due to residual in the yokes. It will be found, however, that the mean values will check very well, even though the differences between the right and the left deflections vary a good deal. Reversed readings, then, always should be taken, and it is better to reverse the magnetizing current than the current in the moving coil.

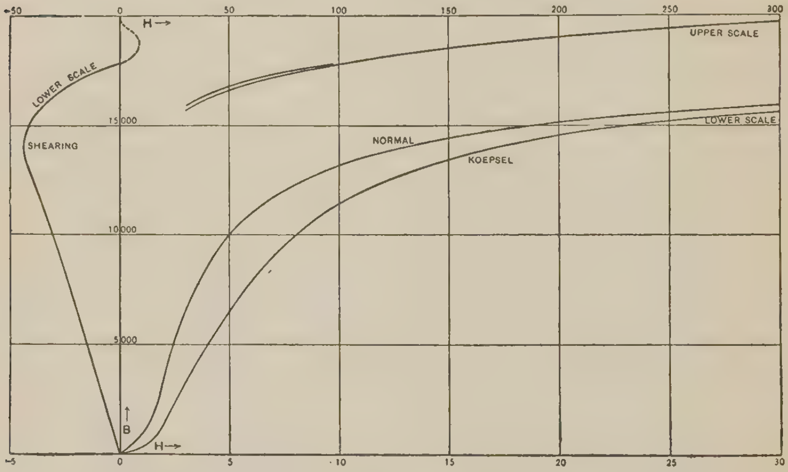

Fig. 150.—Showing the normal induction and shearing curves of a wrought iron rod 0.6 cm. in diameter as measured by a Koepsel permeameter.

Figure 150 shows a typical magnetization curve obtained with a Koepsel permeameter compared with the true values of normal induction. At the left is shown the shearing curve or the amount by which the observed *H* values have to be corrected to give the true values.

Figure 151 shows similar data for several kinds of magnetic material. These show that the shearing curves vary with the kind of material. It also may be noted that they vary with the size of specimen.

These shearing curves are shown not so much to illustrate the errors in this particular type of permeameter as to show the method of obtaining and applying them to other types of commercial permeameters. This is a very useful method of correcting for permeameter errors.

Hysteresis loops obtained on the Koepsel permeameter also show large deviations from the true values. Shearing curves for *Br* and *Hc* may also be determined for any given kind and size of sample.

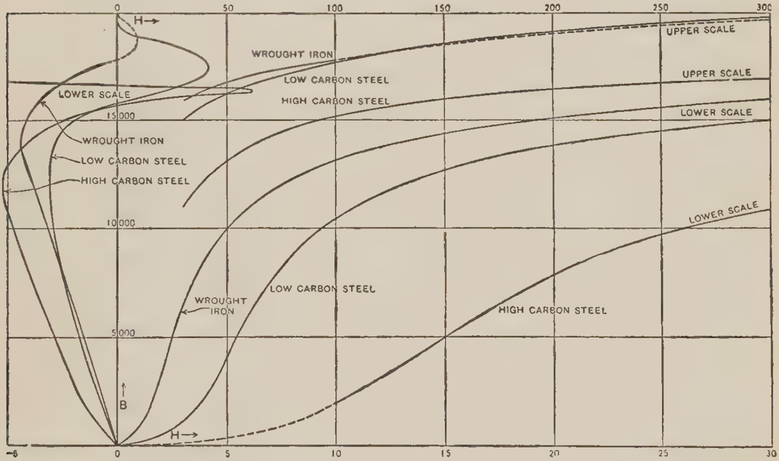

FIG. 151.—Showing normal data and the variation of the Koepsel shearing curve with different materials.

The Koepsel permeameter has the following characteristics, according to Burrows:

1. Readings on two sides of the zero of the instrument may differ considerably, but the mean of the two values thus obtained shows satisfactory consistency on repetition.

2. Shearing curves for different grades of material show that the correction to be applied to the observed magnetizing force is not constant for a given induction, but depends upon the nature of the test specimen. This correction is usually subtractive for points below the knee of the induction curve and additive for points above the knee.

3. An increase in the cross-section of the test specimen tends to increase the observed values of the magnetizing force for points below the knee of the induction curve, and to decrease the observed values for points above the knee.

4. The length of the specimen projecting, beyond the yokes produces no noticeable effect for points below the knee of the induction curve. For points above the knee, the projecting ends increase the observed value of the magnetizing force.
5. Hysteresis loops obtained by the Koepsel permeameter always show a low observed residual induction and a high observed coercive force.
6. With extreme care and the use of proper shearing curves, the apparatus is capable of giving quantitative results within 5 per cent of the true value of the magnetizing force for a given induction.
7. Uncorrected hysteresis data for hard steels show values of the residual induction that are too small; the error may be as great as 10 per cent. Values obtained of the coercive force are systematically too large; the error may be as much as 40 per cent.

A fairly complete description of this permeameter has been given, not because it is particularly accurate, or because it is to be especially recommended, but because it represents one of the best attempts to construct a direct-reading instrument not involving the use of a galvanometer or fluxmeter. The apparatus, accordingly, is rugged and simple to operate. Its chief use should be in connection with the routine testing of large numbers of specimens of approximately the same nature and size, and of moderate or low maximum permeability.

Its chief disadvantage is its inherent inaccuracy and the necessity of using correction factors which depend on the nature and size of the specimen. This makes the apparatus rather undesirable for research work where many kinds of material are involved and only one or, at most, a few specimens have approximately the same properties. Again, where considerable sums of money may be involved and close limits are required in connection with commercial inspection, the highest accuracy is none too good.

Rotating Coil.—Method 4, using the rotating coil, is well illustrated by the Esterline permeameter, which is very similar to the Koepsel, except that the D'Arsonval movement is replaced by a d.-c. armature direct-connected to a d.-c. drive motor which is also attached to a magneto. In determining H, an attempt is made to use method f by means of compensating coils on the poles. When there is no leakage from the ends of the sample, as determined by a magnetometer needle placed close to one end, it is assumed that the compensation is correct. This apparatus reads B, H, and the speed of the rotating armature directly on a single meter by means of transfer switches. B, of course, is proportional to the voltage generated by the armature; and H is proportional to the current in the magnetizing coil surrounding the sample. The magneto reading and therefore the speed is maintained constant. This permeameter is more complicated than the Koepsel apparatus, and according to tests carried on by the Bureau of Standards some years ago has no greater accuracy. Errors in H, unless corrected by shearing curves, are 50 per cent or more in some cases for ordinary magnetic materials.

The rotating-coil method of measuring flux has been used to advantage, lately, by Dellenbaugh[7] to measure the flux in the air-gap of rotating machines. This seems to be a very quick and satisfactory method.

Bismuth Spiral.—The property of bismuth, by virtue of which, method 5, it changes its resistance in a magnetic field, is used only occasionally in experimental work. This method has the double disadvantage that it is sensitive only to large changes in field strength, and the temperature compensation must be very carefully watched as will be evident from the following table:

TABLE XXII.—MAGNETIC-TEMPERATURE-RESISTANCE PROPERTIES OF BISMUTH

Transverse Magnetic Field (Smithsonian Tables)

Kilogausses	0°C.	18°C.	60°C.	100°C.
0	1.00	1.08	1.25	1.42
2	1.08	1.11	1.26	1.43
4	1.18	1.21	1.31	1.46
6	1.30	1.32	1.39	1.51
8	1.43	1.42	1.46	1.57
10	1.57	1.54	1.54	1.62
12	1.71	1.67	1.62	1.67
14	1.87	1.80	1.70	1.73
16	2.02	1.93	1.79	1.80
18	2.18	2.06	1.88	1.87
20	2.33	2.20	1.97	1.95
25	2.73	2.52	2.22	2.10
30	3.17	2.86	2.46	2.28
35	3.62	3.25	2.69	2.45

Polarized Light.—This method (6) has very little application as a test method.[8] It is chiefly of scientific interest and can be applied readily only at high inductions. For a given material, the angle of rotation of the polarized light is directly proportional to the intensity of magnetization J. This coefficient is called the Kerr constant and is different for different materials and different wave lengths.

Ballistic or Fluxmeter Method.—This method (7) of determining B is by far the most common one used, and lies at the foundation of most of the convenient and accurate methods of determining d.-c. magnetic properties available at present. This will be illustrated by a description of the ring test in its elementary form, since this is the simplest and the most accurate method, probably, of determining the magnetic properties of materials, if the samples are available in that form. If the mean radius of the ring sample is sufficiently large, with reference to the radial width of the specimen, the induction and magnetizing force are sensibly uniform and most easily measured with this type of specimen; moreover, there is a minimum of disturbance from any external magnetic fields which may occur.

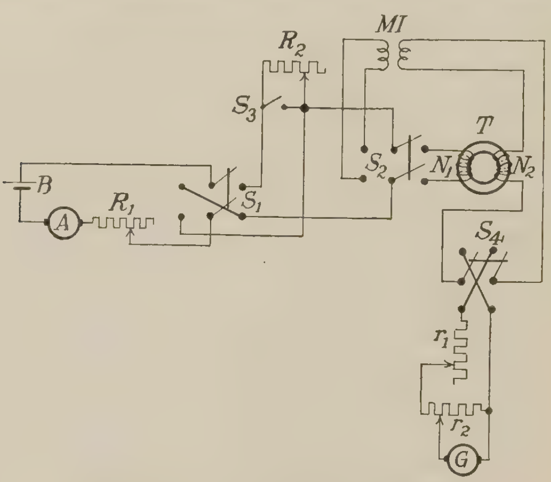

FIG. 152.—Connections for ring test.

Figure 152 is a diagram of connections for the ring test, in perhaps its simplest form. Current from a battery B passes through an ammeter A, variable resistance R_1, reversing switch S_1 to switch S_2. From S_2, it goes to the primary of the mutual inductance MI, if S_2 is thrown to the left, or to the primary winding N_1 of the ring sample T, if S_2 is thrown to the right. The fluxmeter or galvanometer G is connected in series with the secondary of the mutual inductance, the secondary winding N_2 on the sample and the resistance r_1. The resistance r_2 is in parallel with G. For the most convenient manipulation, the series and parallel galvanometer resistances r_1 and r_2 may be so adjusted that a deflection of one main division on the galvanometer scale corresponds to 1 kilogauss of induction in the sample T or a change in induction of 2 kilogausses. This is accomplished as follows: Calculate I_B in this equation:

$$I_B = \frac{N_2AB}{M10^5}, \tag{67}$$

where I_B is the reading of the ammeter;

A is the cross-section of the ring in square centimeters;

N_2 is the number of secondary turns on the ring,

B is the number of gausses for the required deflection. (If the deflection is to be 1 centimeter per kilogauss, B will be 10,000 for a calibrating deflection of 10 centimeters,

M is the mutual induction value in millihenries.

If the ring material is laminated, A is calculated as follows:

$$A = \frac{Wt}{dl}, \tag{68}$$

where Wt is the weight of the sample in grams;

d is the measured or assumed density of the material (usually taken as 7.7 for iron and low-silicon steel, and 7.5 for high-silicon steel; see A.S.T.M. specifications);

l is the mean circumference of the rings in centimeters.

Now, having calculated I_B, set the ammeter A to this value by adjusting R_1 with S_1 and S_2 closed to the left, and S_3 closed. Now, close S_4 and reverse S_1; r_1 and r_2 are then to be adjusted until the desired deflection of G is obtained. The proper values of r_1 and r_2 will be discussed later, in connection with the characteristics of galvanometers and fluxmeters. Now, throw S_2 to the right and increase the reading of A until the galvanometer G indicates an induction above the point of maximum permeability, when S_1 is reversed. Then, decrease the current gradually by increasing R_1, and at the same time keep reversing S_1 slowly in order to demagnetize the sample. For small samples of high-resistance, laminated material, these reversals may be rapid, but for large samples of low-resistance material the reversals should be slow, and especially so if the material is solid. By observing the action of G while reversing, it will be evident whether or not slow reversals are desirable.

Normal Induction Data.—When the demagnetization has been completed to the lowest value required, then proceed to the determination of the normal induction data. H is obtained from the reading of the ammeter A from the following equation:

$$H = \frac{0.4N_1I}{D}, \tag{69}$$

where H is in gilberts per centimeter;

N_1 is the number of primary turns on the sample;
I is the current in the primary in amperes;
D is the mean diameter of the sample in centimeters.

The ammeter is now set corresponding to the desired value of H_1, S_1 reversed a few times to put the sample in a cyclic condition, and the galvanometer G set on zero by one of a number of means to be described later. S_1 is then reversed and the deflection of G noted. This gives the induction B directly in kilogausses. S_1 is then increased and the procedure repeated until the desired number of points on the curve have been obtained. If the values of H for even values of B are desired, they may be obtained from the curve. Due to the shape of the magnetization curve, it will be found desirable not to take evenly spaced values of H, but to increase the intervals. For instance, the following values might be found convenient: $H = 1, 2, 4, 10, 20, 40, 100$, etc.

In order to make H direct-reading, N_1 may be so chosen that $H = 10I$. In order to do this, it is necessary to have the following relation:

$$\frac{0.4N_1}{D} = 10; \tag{70}$$

or,

$$N_1 = \frac{10D}{0.4}. \tag{71}$$

If it is not convenient to make $H = 1$, or some multiple, by 10, a special scale may be placed on the ammeter to suit, if a considerable number of samples of the same diameter are to be tested. $H = 3I$ is a very convenient range.

Hysteresis Loops.—In order to obtain hysteresis loops, the procedure is as follows: If it is desired to make G direct-reading, it should be calibrated for twice the sensitivity used for the magnetization curves; namely, a deflection of 20 instead of 10 divisions; or else, the galvanometer readings must be multiplied by two. Now, referring to Fig. 153 which represents a normal hysteresis loop, it may be assumed that B_m and H_m, the coordinates of the tip of the loop, have been obtained from a point on the normal induction curve. Adjust the ammeter A (see Fig. 152) to give H_m and reverse S_1 a few times, in order to put the sample in a cyclic condition. Throw S_1 to the right and reverse S_4, in order to keep the galvanometer deflections in the same direction. Then open S_3 and note the galvanometer deflection. Assuming that R_2 is so adjusted as to reduce H_m to H_1, the galvanometer deflection will be ΔB_1. B_1 is, then, $B_m - \Delta B_1$, giving the point (1) on the hysteresis loop. As many points as desired down to zero H may be obtained in this way by varying R_2.

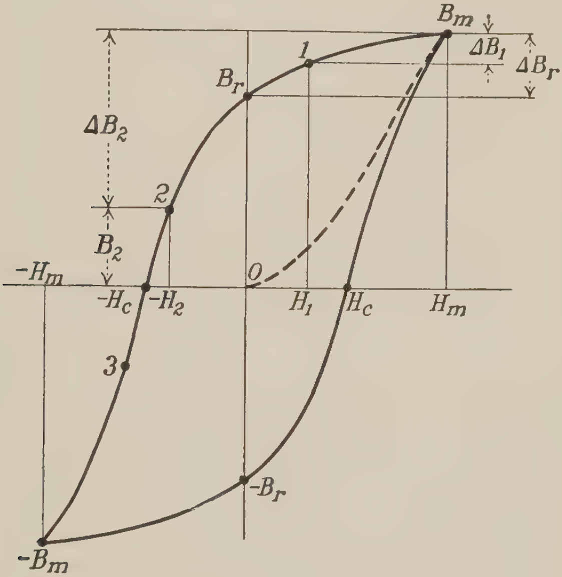

FIG. 153.—Hysteresis loop illustrating ballistic method of test.

In order to obtain the retentivity B_r, S_2 is opened giving ΔB_r as the galvanometer deflection; then $B_r = B_m - \Delta B_r$.

For points corresponding to negative values of H, such as point (2), again reverse S_4 and start with S_1 at the left and S_3 open. Now, reverse S_1 and note the galvanometer reading, which will be ΔB_2; H being given by A. The manipulation of switch S_2 first reduces H to zero and then applies a negative value H_2. As many negative H points as desired, such as (3), may be obtained by varying R_2. The coercive force H_c may be obtained by plotting the hysteresis loop, or directly by adjusting R_2 until $\Delta B = B_m$ and then noting the ammeter reading A. It will be noted that all points are obtained independently by starting with the tip value, and that both the upper and the lower tips are used, the choice depending on which is more convenient. This is permissible because the loops are symmetrical. It will be seen that, since each point is obtained with reference to the tip, there are no cumulative errors, such as were common with the old step-by-step method. In order to maintain the continuity of the loop, it is best to return to the tip by following around the loop instead of introducing a minor loop by going directly back to the tip. After obtaining point (1), for instance, reverse S_1, close S_3, and again reverse S_1, thus returning to B_m. If S_3 is immediately closed, a minor loop is traced, and in this case S_1 should be reversed several times before obtaining the next point on the loop. For a point such as (2), close S_3 and then reverse S_1, in order to return to the tip without introducing a minor loop.

After obtaining the hysteresis loop, if the hysteresis loss is required, it may be determined from the area as measured by means of a planimeter (see formula (23) Chap. III). If the maximum induction is 10 kilogausses, the two H values corresponding to $B = 8$ kilogausses and the H_c value may be measured, and the hysteresis loss estimated fairly closely from formula (30), page 22. Or, by simply obtaining H_c corresponding to a particular value of B_m, the hysteresis loss W_h may be calculated approximately from the data of Anderson and Lance (see p. 22), or by Gumlich's refinement (see p. 22).

If the details of this simple ring test are understood, the principles and methods of operation of several of the better-known commercial permeameters which make use of the ballistic method can easily be made clear. It is for this reason that this particular method of test has been described somewhat minutely.

Obviously, if the material is in the form of a long rod or wire, an identical test to that for the ring sample may be used by employing a long solenoid within which the sample is placed. The circuits and procedure may be the same except that the effect of the earth's field should be eliminated, as for the magnetometer method. H is given by formula (61), page 206. If the length of the rod is not several hundred times its diameter, H, as calculated from this formula, will be the apparent value and must be corrected for the demagnetizing effect of the sample ends by using the data of Fig. 43, for instance (see p. 61). For further details concerning the ballistic method, Chap. XVIII should be consulted.

Multiple-ring Test.—For research work on magnetic materials where it is permissible to use small samples and where many samples are to be tested, and especially when material of exceptionally high maximum permeability and low coercive force are to be tested, the ballistic-ring method of test is particularly useful. In his development of improved magnetic materials, Yensen made use of several thousand ring samples which were tested by the arrangement shown in Fig. 154[9], as described some years ago,[9] and since somewhat modified.

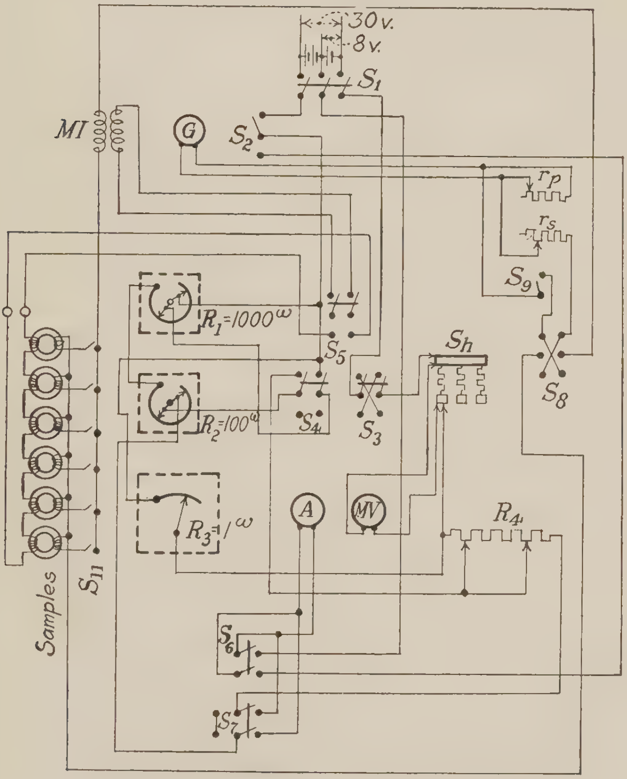

FIG. 154.—Connections for multiple ring test.

In general, for solid material, ring samples $^{31}/_{32}$ inch outside diameter by $^{23}/_{32}$ inch inside diameter by $^{3}/_{8}$ inch thick are used. These rings are wound with 16 primary turns and 20 secondary turns. In order to increase the speed of testing, several rings may be tested together with their primary windings connected in series. One end each of their secondary windings are connected together, and the other ends connected to single-pole switches, so that one after the other may be connected to the galvanometer as indicated by Fig. 154. If more convenient, a single primary winding for several samples may be used, by winding the rings with their several secondaries, then stacking them one above the other, and applying a single primary winding around the whole.

For laminated material, usually, samples are punched having an outside diameter of 1.75 inches and an inside diameter of 1.25 inches. About 50 grams of punchings make a convenient weight of sample. This weight requires about 10 secondary turns and 29 primary turns for the available fluxmeter sensitivity and a mutual inductance value of a little over 0.6 millihenries.

The current is supplied from a 30-volt battery with a tap at 8 volts as indicated. With switch S_2 down, the 8-volt section is used; and with S_2 up, the whole battery is connected. S_3 is the reversing switch. S_4, when thrown down, introduces the necessary resistance for obtaining hysteresis-loop data. S_5, when up, connects the battery and ammeter A to the primary of the mutual inductance for calibrating purposes, and when down, connects to the primary of the samples. The resistances R_1, R_2, and R_4 are in series. R_1 is for the coarse adjustment, R_4 for the fine, and R_2 is intermediate. It will be seen that each of these resistances has two taps. Throwing switch S_4 down, introduces the portion of the resistances between taps into the primary circuit thus decreasing the current for hysteresis determinations. R_3 is a parallel resistance of high current-carrying capacity used for H values of over 30 gilberts per centimeter and is ordinarily not in circuit. The ammeter A and the millivoltmeter shunt Sh are in series when switch S_2 is down. The ammeter A and the millivoltmeter MV are calibrated to read H directly; namely, the primary windings are of such a number of turns that $H = 3I$. The ammeter A, therefore, which gives a full scale reading for 1 ampere has 30 main divisions, each division corresponding to one-tenth gilbert per centimeter. The millivoltmeter MV also has 30 main divisions, and is marked in 1 gilbert per centimeter steps. It reads directly for the most sensitive connection to its shunt. The other two shunt connections may be for any convenient multiples. It should be noted that when S_2 is down, the ammeter and millivoltmeter shunt are in series, but when the higher voltage is applied by throwing S_2 up, the ammeter A is automatically cut out of circuit.

Under normal operation, S_6 is closed, and S_7 is closed to the left. When, however, hysteresis data are required from fairly high magnetizing forces, the readings of MV would be too small to give accurate values in the region of the coercive force. Under these conditions, S_6 is opened and S_7 is thrown to the right. With this arrangement, the more sensitive ammeter A is in series with the shunt Sh, when S_4 is thrown down but is short-circuited, and therefore protected when S_4 is thrown up, that is when going to the tip of the hysteresis loop.

The secondary connections are obvious. The fluxmeter or galvanometer G is in series with the secondary of the mutual inductance MI and with one of the sample secondary windings depending on which of the S_{11} switches is closed. The fluxmeter is shunted by the resistance r_p, in series with which is the resistance r_s. S_9 opens the galvanometer or fluxmeter circuit, and S_8 reverses the polarity of the fluxmeter.

In order to calibrate the fluxmeter, S_2 is thrown down and S_5 up. The ammeter A is then in series with the primary of the mutual inductance. The current is then adjusted to one ampere (full scale for A) and r_p and r_s adjusted until G gives 10 centimeters deflection when S_3 is reversed. Then with S_5 thrown down, the current is adjusted until ammeter A indicates the desired value of H. The first S_{11} switch is closed, S_3 reversed, and the fluxmeter deflection noted when S_2 is reversed. Then with S_2 thrown down, the induction B is indicated directly in kilogausses, corresponding to the given H. This is repeated, closing the S_{11} switches one at a time with the others open. This gives all of the B values corresponding to the given H value. The process is then repeated for the other desired values of H.

The procedure for the hysteresis determinations will be obvious from the preceding explanation and the description of the simpler form of ballistic ring test. For the hysteresis data it is usually desirable to calibrate for 20 instead of 10 centimeters in order to eliminate the necessity for multiplying the ballistic readings by two.

If sufficiently large wire is used for the primary windings on the samples, H values of 300 gilberts per centimeter can be readily obtained. With 10 samples connected up together, the complete data for an 11-point magnetization can be easily obtained in 4.5 minutes per sample and 12-point hysteresis loops can be determined in 6 minutes per sample. A sample can be wound in 10 minutes.

Since the samples are so small, machining or punching strains must be eliminated by annealing before testing. This is no handicap, however, since some sort of heat-treatment is a part of the program for research work anyway. Due to its simplicity, accuracy, speed, and the small size of samples required, this method of test is to be preferred for research work on samples of laboratory-prepared material.

As described in the above-mentioned article,[9] S_3 and S_4 may be operated by foot levers, if desired, thus leaving the hands free for recording data and operating the other switches. Methods of obtaining a long scale distance, without taking up space in the room, by using mirrors and right-angled prisms are also described.

The battery, the switches S_2, S_3, S_4, S_5, S_6, S_7, and the shunt Sh should be capable of handling at least 100 amperes in order that high magnetizing forces may be obtained without requiring a large number of primary turns on the samples. R_3 is used only for the large currents and must not be in circuit when obtaining hysteresis data.

Constant-voltage Method.—If a specimen of magnetic material is surrounded by a coil of wire which is connected to a voltmeter or galvanometer, and the magnetic flux in the specimen is caused to change at a constant rate, the voltmeter will give a constant deflection. If the voltage is 1 volt, the change of linkages (product of number of turns by change of flux in maxwells) must be at the rate of 10^8 per second. Figure 155 illustrates a method of magnetic testing employing this principle.

A circular rheostat is supplied with current at two diametrically opposite points from the battery B_1, through a regulating resistance R_1. The primary of the test sample N_1 is connected through an ammeter A and resistance R_2 to the rheostat, as indicated. If the rotating contact C starts at a, the current in N_1 will be zero. If it revolves as shown, the current will increase to a maximum at b, decrease to zero at c, increase in the opposite direction to a negative maximum at *d*, and back to zero at *a*. If the sample is in a neutral state at the start, a normal induction curve will first be traced and then one complete side of a hysteresis loop.

Now, suppose the secondary winding N_2 on the sample is connected through a resistance R_3 to the galvanometer *G*, and suppose one millivolt causes a deflection of 10 centimeters. This adjustment may be made by throwing switch *Sw* to the right, adjusting R_4 for a reading of 1 millivolt on millivoltmeter *V*, and adjusting R_3 until *G* shows a deflection of 10 centimeters. Now, if N_2 has 100 turns, the cross-section of sample *S* is 1 square centimeter, and *Sw* is thrown to the left; the arm *C* may be moved at such a varying rate that the deflection of *G* is held constant at 10 centimeters. This means that (since the cross-section of the sample is 1 square centimeter) the flux density *B* changes at the rate of 1 kilogauss per second. If, then, *A* is read once a second, the *H* values will be obtained corresponding to each kilogauss change of induction. Obviously, the sensitivity of *G* may be altered to give any desired rate of change of flux. R_2 and R_3, of course, are adjusted to give the desired maximum induction when the arm *C* is at *b* or *d*.

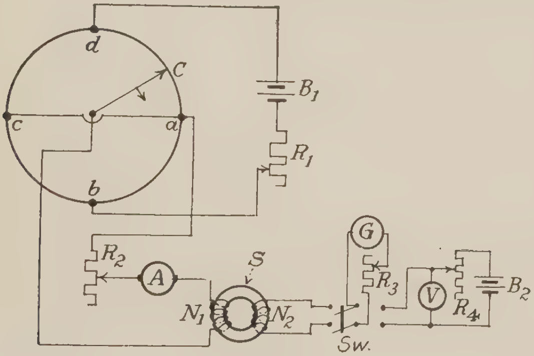

FIG. 155.—Constant voltage magnetic tester.

One of the early applications of this method was made by Professor Scott for the purpose of measuring the magnetic properties of the fields of the first Niagara Falls generators. In that case, the mass of the core material was so great that a low-reading voltmeter could be used, instead of the galvanometer.

1. A Sensitive Magnetometer Insensitive to Extraneous Disturbance, E. P. T. Tyndall, *Jour. O.S.A. and R.S.I.*, p. 465, October, 1924.

2. Methods of Measuring the Effect of Temperature on Magnetic Properties, Earle M. Terry, *Jour. O.S.A. and R.S.I.*, vol. 11, 1, p. 67, July, 1925.

3. Ewing, p. 259; "American Handbook for Electrical Engineers," p. 918; "Standard Handbook for Electrical Engineers," p. 188.

4. Ewing, p. 374; "American Handbook for Electrical Engineers," p. 919.

5. Magnetic Testing of Iron, W. H. F. Murdock, *Jour. I.E.E.*, vol. 40, p. 137, 1907–1908.

6. A Direct Recording Method of Measuring Magnetic Flux Distribution, F. S. Dellenbaugh, Jr., *Jour. A.I.E.E.*, p. 583, June, 1920.

7. An Experimental Study of the Koepsel Permeameter, C. W. Burrows, *Bur. of Standards Sci. Paper*, 228, Aug. 1, 1914.

8. Ewing, p. 158, 3d ed.

9. The Rapid Determination of the Magnetic Properties of Materials, Thomas Spooner, *Elect. World*, p. 4, July, 1919.

CHAPTER XVI

COMMERCIAL D.-C. PERMEAMETERS USING BALLISTIC METHOD

In the preceding chapter the ballistic method of measuring induction has been described in some detail, and the principle of its use illustrated by a fairly detailed description of the ring test. Now, its use will be further illustrated by describing certain types of commercial permeameters which are in use at present, or which have in the past met with more or less favor. A knowledge of the advantages and limitations of these various types of tests is desirable when making a choice of a method for some particular application. Absolute accuracy, reproducibility of results, simplicity and speed of operation, cost of preparing test samples, desired range of inductions or magnetizing forces, and, perhaps, some other factors have to be considered; the relative importance of these factors depending on the application.

Commercial permeameters, in general, use a straight sample or samples, the ends of which are joined by some sort of yoke. Magnetizing windings may surround the sample, the yoke, or both. Usually, the chief concern of the permeameter designer is to dispose his windings, so that the reluctance of the joints between the samples and yokes may be compensated for, so that approximately uniform flux exists in the samples over the length which is to be measured. The *H* values then may be determined from the magnetizing forces applied to the samples, as calculated from the ampere-turns in the magnetizing windings if there is perfect compensation, by determining the amount of the total applied magnetizing force necessary to overcome the gap and yoke reluctances, by a modification of the Chattock magnetic potentiometer, or by other means which will be described presently.

Hopkinson Divided-bar Method.—In this method[1] the sample consists of two bars which are butted together and inserted in a massive U-shaped yoke. A magnetizing coil surrounds each of the sample bars. A small exploring coil, located between the magnetizing coils and around the bars at the buttjoint, is connected to a ballistic galvanometer. When one of the test bars which has an eyebolt inserted in one end is pulled out, thus opening the joint, the exploring coil is jerked out from the sample by means of a spring, and the induction which existed in the sample is given by the deflection of the ballistic galvanometer. The magnetizing force is estimated from the current in the magnetizing coils. Obviously, H cannot be calculated accurately, but may be determined roughly by calibrating the apparatus with samples having known magnetic characteristics. Evidently, the effective value of H is a function of the condition of the air-gaps, both between bars, and between bars and yoke. This, of course, will vary from sample to sample, the magnitude of the effect depending on the induction. The advantage of this method is that the field does not have to be reversed. For high inductions, this may be a real advantage. The chief disadvantages are the inherent inaccuracies in determining H and the necessity for preparing accurately ground-test samples. The apparatus is now practically obsolete.

Ewing Double-bar Method.—Ewing undertook to eliminate the effects of the yoke and joint reluctances by using two bars machined to fit closely in two yokes.[2] He first measured the magnetic properties with the yokes in one position, and then increased their distance apart by some definite amount, say double, and made a new measurement of the magnetic properties (see Fig. 156). In each case the bars were surrounded by magnetizing coils extending over the full length and having a definite number of turns per unit of length. Obviously, if the reluctance of the joints was the same in both cases, the difference in magnetizing force between the first case and the second for a given induction would be due to the reluctance of the extra length of samples, and thus would give a means of correcting for the yoke reluctance. This method has the disadvantages that

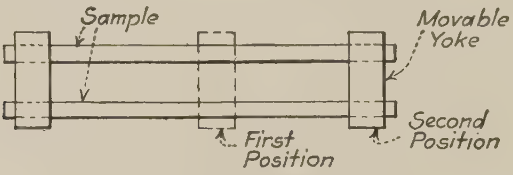

FIG. 156.—Ewing double-bar method.

the joint reluctances and leakage conditions are never quite the same for the two positions; that two carefully machined duplicate uniform samples are required; and two sets of data must be determined. Two perfectly uniform samples are impossible to obtain and, of course, the joint reluctances can never be identical. This method is, therefore, no longer used to any extent.

Picou Permeameter.—The essentials of this permeameter[3] are illustrated by Fig. 157. The principle of this instrument is rather ingenious, which is the chief reason for describing it. Two similar yokes, Y_1 and Y_2, are provided with magnetizing windings A and B. The sample N, also provided with a magnetizing winding M, is placed between the yokes as indicated. The coils A and B are first connected in series through a battery, ammeter, and reversing switch, so that the yoke fluxes are in series. If the reluctances of all four joints are equal, and if the reluctances of the two yokes are equal, no flux will pass through the sample. The yoke flux is measured by means of an exploring coil and ballistic galvanometer. One of the coils, A or B, is then reversed, current applied to the winding M and adjusted until, on reversing the yoke and sample magnetizing currents, the yoke flux is the same as before reversing the A or B connections. Under theoretically perfect conditions, the current in A and B will, then, just supply sufficient m.m.f. to overcome the reluctance of the yokes and joints, and the current in M will give the H value for the sample.

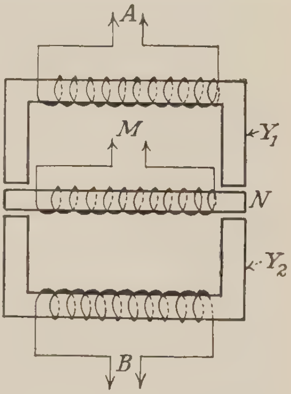

FIG. 157.—Picou permeameter

This method has two drawbacks. First, the method is rather tedious; second, the two yoke reluctances and the four gap reluctances never have the necessary conditions of equality. Burrows has shown experimentally that this apparatus is subject to appreciable errors at high inductions.

Searle Permeameter.—Searle attempted to use the well-known hollow-square arrangement of samples for permeability testing, which was later used so successfully by Epstein for core-loss measurements, except that for laminated material he used alternating lapjoints and buttjoints instead of straight buttjoints, as is the case for the Epstein test.[4] Even a lapjoint has considerable reluctance, which Searle tried to neutralize by applying compensating windings adjacent to the corners. These compensating coils were in series with the main magnetizing coils, and were adjusted so that a small compass needle adjacent to the joints showed a condition of no appreciable leakage. This apparatus is rather inaccurate, at least for moderate inductions, since the four joints are never identical and cannot be compensated for flux leakage in all planes simultaneously. This arrangement is more satisfactory at high than at moderate inductions, and will give fair results even with no compensating windings in the former case. The method of determining the condition of compensation for joint reluctance by observing the position of a small magnetic needle has been used in a number of other permeameters and has never proved altogether satisfactory or reliable.

Iliovici Permeameter.—This permeameter[5] eliminates the effect of joint reluctance by a compensation method, and the state of compensation is determined by means of a modification of the Chattock magnetic potentiometer, the modification consisting in using a core of ferromagnetic material for the potentiometer, the original Chattock potentiometer having an air core. The arrangement is shown by Fig. 158. The yoke *Y* is provided with a magnetizing coil *A* connected to a battery through a reversing switch. The sample is indicated by *S* and is provided with a uniformly wound magnetizing winding *M*, also connected to a reversing switch and battery. The sample is also surrounded by an exploring coil *N*. The magnetic potentiometer consists of the core *P* surrounded by the exploring coil *G*.

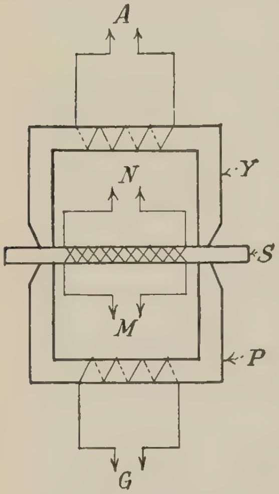

FIG. 158.—Iliovici permeameter.

The principle of operation is as follows: For a given current in the magnetizing winding *M*, the current in the yoke winding *A* is so adjusted that, on simultaneously reversing both currents, a fluxmeter or ballistic galvanometer connected to the potentiometer circuit *G* will show no deflection. This means that the reluctance of the joints and yoke *Y* are compensated for by the current in A, and the current in M supplies just enough m.m.f. to overcome the reluctance of the sample S over a length equal to the distance between the centers of the joints between the sample and potentiometer. H is then calculated from formula (61), or the ammeter in series with M may be calibrated to read H directly. The induction B in the sample is obtained by reversing the currents and noting the deflection of the fluxmeter or galvanometer connected to the terminals of N.

Theoretically, this permeameter should give very reliable results. As actually constructed, it has one bad feature for certain applications. The test specimen is only about 1 centimeter square. For samples of sheet material which are not to be annealed before testing, the strips would be so narrow that the magnetic quality at moderate inductions would be very poor, due to punching strains (see Chap. VIII). It is desirable that a permeameter be capable of taking samples of at least Epstein width (3 centimeters or 1$\frac{3}{16}$ inches).

Niwa Permeameter.—In an attempt to overcome the defects inherent in many of the existing permeameters, a permeameter has recently been developed in Japan by Niwa,[6] the action of which is based on the principle of the Chattock magnetic potentiometer. The general arrangement is shown by Fig. 159, the coil connections by Fig. 160, and the external connections by Fig. 161. Two similar magnetic specimens S and T, are joined magnetically by the yokes Y. S is the sample under test. The auxiliary test piece T does not need to be identical, but should not differ from S to any large extent. The main magnetizing windings M_s and M_T are connected in series with the auxiliary windings M_c and M_t through suitable control switches, rheostats and battery. The yoke windings M_y are connected in series with another similar circuit. The magnetic potentiometer G consists of a large number of turns of very fine wire wound on a nonmagnetic core but provided with magnetic extension pieces which butt against the sample S. Surrounding the sample S is wound an exploring coil m for determining the induction.

The principle of operation will be made clear by the following description. Sufficient current is supplied to the sample windings M_s to give the desired value of H as determined from the number of turns and length of M_s using formula (61). The ammeter in this circuit may be arranged to read H directly if desired. Current is then applied to the yoke windings Y

and so adjusted that, when the main and yoke currents are reversed no residual deflection is shown by the fluxmeter, which in this case is connected by the switch *K* to the potentiometer coil *G*. Under these conditions all of the m.m.f. required to overcome the reluctance of the sample *S* between the potentiometer terminals is supplied from coil M_s and therefore is subject to simple calculation. In other words, the reluctance of the yokes, joints, auxiliary bar *T*, and the portion of the bar *S* not between the potential terminals is compensated for by the other coils, and *H* is calculated from the number of turns per unit length of M_s, as for a simple ring sample. The fluxmeter is then switched to the exploring coil *m*, the primary

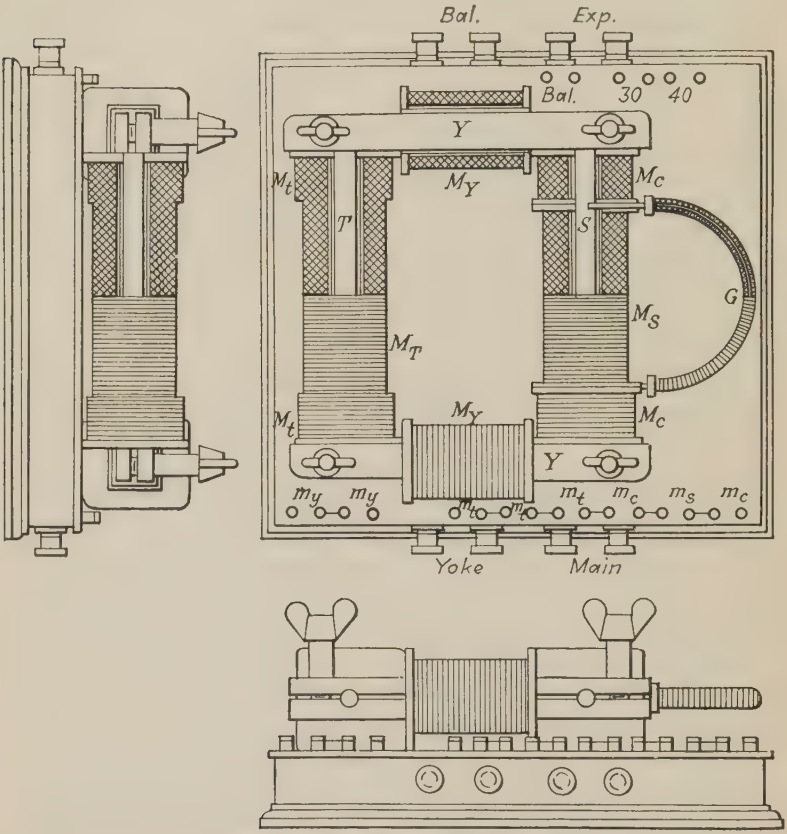

FIG. 159.—Diagram of Niwa permeameter.

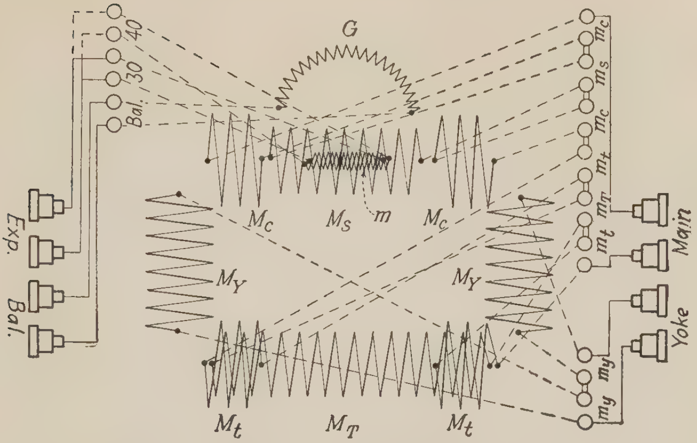

FIG. 160.—Internal connections of Niwa permeameter.

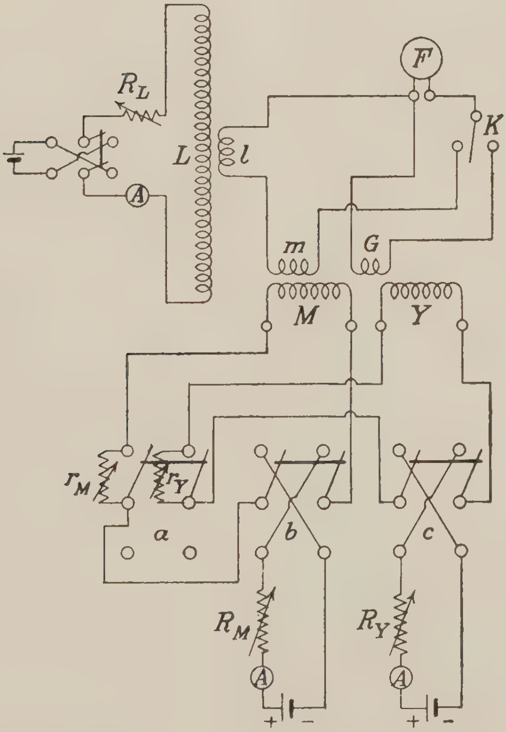

FIG. 161.—External connections of Niwa permeameter.

currents reversed and the induction B determined from the fluxmeter reading. The fluxmeter is calibrated in the usual way by means of a mutual inductance.

The method of obtaining hysteresis data will be obvious from Fig. 161, and the previous explanation with reference to the ring test. The currents in M_s, etc. and M_y are reduced, or reduced and reversed simultaneously, and so adjusted that, with the fluxmeter connected to the potentiometer G, no residual deflection is shown. The procedure is then exactly like that for a ring test.

Comparison tests against the Burrows permeameter on a sample of moderate permeability show excellent agreement. No very complete checks on this apparatus have been reported, but the principle seems to be correct and, from Niwa's experimental analysis of the flux distribution under various conditions, this should be a very satisfactory instrument. It will be referred to again when considering the Burrows and Fahy permeameters. Niwa's original article should be consulted for a very complete description of the principle of the instrument and a critical discussion of various types of permeameters in general.

Cioffi Permeameter.—Cioffi has recently developed an instrument for measuring the magnetic properties of materials having a high initial permeability. It is confined to materials having a wire or ribbon form, but has some interesting features which deserve mention, especially since it deals with samples of very small cross-section and, at the same time, has very high sensitivity for low inductions. According to the author,[7] in addition to "its particular application to the study of strain effects, it furnishes a convenient means for applying and measuring any desired succession of magnetizing processes, and without essential modification lends itself to temperature control over a wide range, and to a study of changes due to chemical processes, cold working, and heat-treatments."

The main magnetizing coils P_1 and P_2, the search coil, and an arrangement for studying the effect of tension on magnetic properties are shown by Fig. 162; and Fig. 163 shows the details of the search coil. For a wire 1 millimeter in diameter, the dimension ratio is 600, so that no appreciable errors result from end effects. The connections are shown by Fig. 164. The search coil is C_s. P_cC_c is a mutual inductance for calibrating purposes, the primary being supplied through reversing switch S_5. The

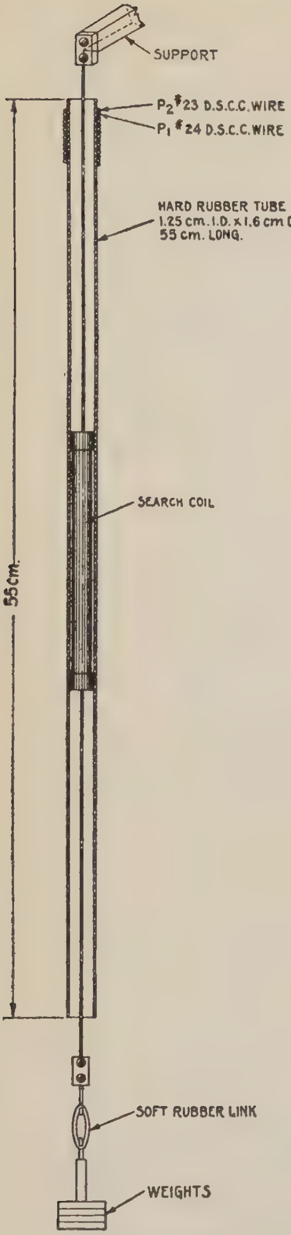

Fig. 162.—Cioffi permeameter: Magnetizing and search coils and means of applying tension to specimen.

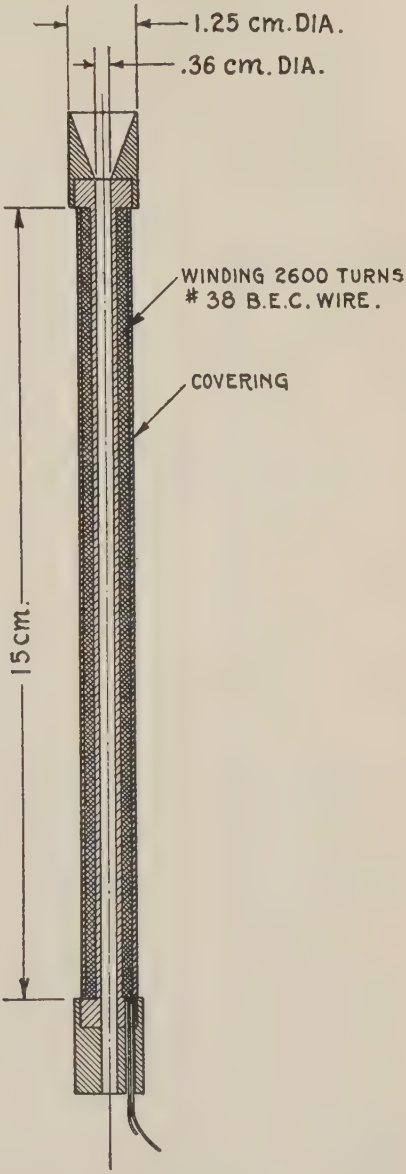

Fig. 163.—Cioffi permeameter: Details of search coil.

main magnetizing current is supplied through switch S_1. With this switch thrown to the left, the magnetizing current is adjusted by means of the resistance R_1, the turns on the primary winding P_1 being so adjusted that the ammeter A_1 reads H directly. By reversing S_1, R_1'' is introduced, thus giving a reduction and reversal of the magnetizing current simultaneously. Further changes may be effected by opening or closing S'_1. If still further alterations in H are required, they may be obtained by applying current to P_2 through switch S_4 (left) and S_2 (right). By this means, two tip values of a displaced loop may be maintained and points in between readily obtained. Also, if desired, alternating current may be applied through S_3.

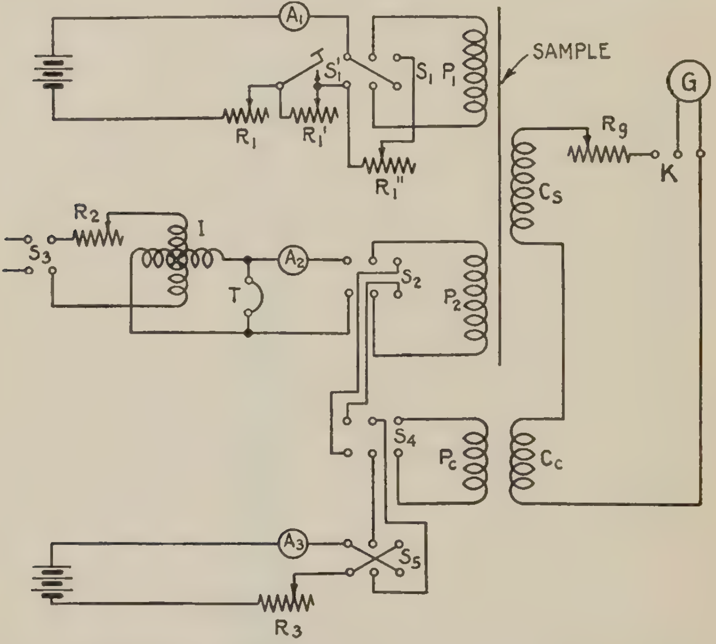

FIG. 164.—Diagram of connections of Cioffi permeameter for ballistic measurements.

Magnetizing forces from zero to 10 gilberts per centimeter are obtainable with this apparatus, and sufficient induction sensitivity is available with samples having a cross-section of 0.01 cm.^{2} only, due to the large number of secondary turns. If desired, the same primary connections could be applied to ring specimens, but the induction sensitivity could not be readily obtained, since the winding of a large number of secondary turns would be very laborious.

1. "Standard Handbook of Electrical Engineers," p. 186.
2. Ewing, 3d ed., p. 362.
3. Picou Permeameter, A. Campbell, *Electrician*, vol. LVIII, p. 123, 1906. Electrical Measurements in Practice, by Farmer, p. 330.
4. Studies in Magnetic Testing, Searle, *Jour., I.E.E.* 34, p. 55, 1904.
5. Iliovici, *Bul. Soc. Int. des Elect.* 3d ser., 3, p. 581, 1913.
6. A Null Method for Testing Magnetic Properties of Materials, Y. Niwa, *Researches of the Electrotechnical Laboratory* 142, Ministry of Communications, Tokyo, Japan.
7. Magnetic Measurements on Materials of High Initial Permeability, P. P. Cioffi, *Jour. O.S.A. and R.S.I.*, vol. 9, p. 53, July, 1924.

CHAPTER XVII

BURROWS AND FAHY PERMEAMETERS—COMPARISON METHODS—OTHER TEST METHODS

Of the various permeameters making use of the ballistic galvanometer or fluxmeter, there are two which have far outdistanced all others for popularity in America. They are the Burrows permeameter and the Fahy Simplex permeameter, the latter being the more recent. Due to their rather wide use, they will be described in considerable detail. They operate on different principles, and each has certain applications for which it is best suited.

Burrows Permeameter.—In 1909 Dr. Burrows, then at the Bureau of Standards, described the permeameter which is named for him.[1] Very soon afterward, it was generally adopted in the United States as the standard instrument for obtaining the d.-c. magnetic characteristics of materials. This recognition of the value of the apparatus was expedited by the fact that the Bureau of Standards adopted it and the American Society for Testing Materials specified it as the standard method of test. It will be described, therefore, in several of its modifications; and various arrangements of the auxiliary equipment which have proved advantageous will be considered.

Principle of Operation.—This permeameter requires two samples of approximately the same dimensions and having somewhat similar magnetic characteristics. If the two samples are sufficiently alike, so that a mean of their properties is satisfactory, the operation of testing is considerably simplified, as will be shown presently.

Referring to Fig. 165, the samples M_1 and M_2 are connected magnetically by the yokes YY. If only one sample is to be tested, it is M_1, M_2 being the auxiliary sample. Surrounding the samples and wound on suitable nonmagnetic supporting tubes are the exploring coils t, a, j_1, j_1, j_2, j_2. The diameter of the coils should be as small as possible, allowing only sufficient space for mechanical clearance and insulation. If the coils t and a, which must be alike, each have 100 turns, the coils j_1, j_1 and j_2, j_2 must each have exactly 50 turns. The j_1 coils are connected permanently in series as shown, as are also the j_2 coils. The j coils should be spaced about midway between the center and the yokes, or perhaps a little farther apart toward the yokes. They must not be too close, however, to the yokes, or, the compensation will be incorrect. Outside of the exploring coils are the main primary windings T and A. These may be most conveniently arranged with 10 layers each. The turns must be spaced uniformly. If the insulating tubes on which they are wound are accurately grooved on a lathe, the winding will be greatly facilitated.

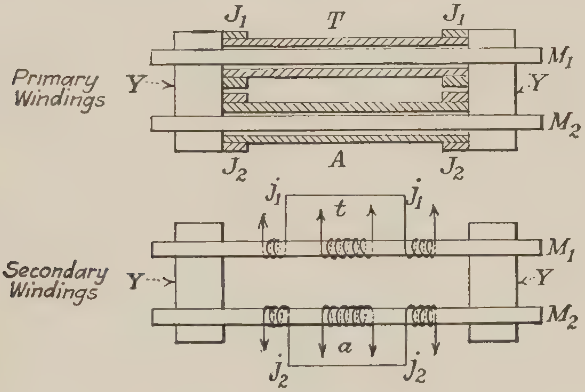

FIG. 165.—Burrows permeameter yokes.

Outside of the coils T and A are placed the compensating coils J_1, J_1, J_2, J_2 as indicated. These coils may consist of three or four layers of 15 or 20 turns per layer. In one form of yokes the main coils are shortened on a diagonal, and at the yokes the J coils occupy the full depth of the main winding. The four J coils are connected permanently in series.

The function of these various coils is as follows. If there were no J coils present, a part of the m.m.f. supplied by the T and A coils would be used up in overcoming the reluctance of the joints and yokes. This reluctance, of course, is, subject to considerable variation, as affected by the dimensions of the samples, method of clamping, etc. If, however, sufficient current is passed through the J coils, the necessary m.m.f. may be supplied by them for overcoming these reluctances and the total m.m.f.

of the T and A coils then will be used to magnetize the samples M_1 and M_2. Under these conditions,

$$H = 0.4\pi N_c I, \tag{72}$$

where H is in gilberts per centimeter,

N_c is the number of turns per centimeter in the T and A coils,

I is in amperes (current in T).

In order to determine when the compensating current in the J coils is sufficient, assuming that the sample M_1 is under test, the coils j_1, j_1 are connected in series with, and opposing, coil t through a fluxmeter. If, now, the currents in the T, A, and J coils are reversed simultaneously, the fluxmeter, in general, will, show a residual deflection due to the fact that there is either more or less flux threading the t coil than the j_1j_1 coils, as a result of over-compensation or under-compensation for the joint and the yoke reluctances. In other words, there is a certain amount of leakage flux through the air. If, however, the currents in the JJ coils are properly adjusted, there will be uniform flux in the sample M_1, except close to the yokes, and the magnetizing force H may be calculated from formula (72). This condition of uniformity of flux is indicated when, with the t and j_1j_1 coils connected in series opposing, the fluxmeter shows no residual deflection. By connecting the fluxmeter to the coil t and noting the deflection when the magnetizing currents are reversed, the induction in sample M_1 may be determined.

There are two types of test—the so-called precision method in which only the sample M_1 is tested, and the American Society for Testing Materials test in which the mean properties of the two samples M_1 and M_2 are obtained. In the former case the current in coil T is adjusted to give the desired value of H, as indicated by an ammeter; and the current in A is then adjusted until there is the same flux in samples M_1 and M_2. This is determined by connecting the exploring coils t and a in series opposing, through a fluxmeter, reversing the current through T and A simultaneously, and adjusting the current in A until no residual deflection is shown by the fluxmeter. (Due to eddy-currents in the samples and yokes, the fluxmeter may show a double kick. Attention should be paid only to the final position.) Uniformity of flux in sample M_1 is then obtained by bucking coils t and j_1j_1 as explained above. The induction is then determined from coil t by connecting it alone to the fluxmeter.

In the American Society for Testing Materials method the coils T and A are connected permanently in series, coils t and a are connected permanently in series, and the four coils j_1, j_1, j_2, J_2, are connected permanently in series. The coils t and a are connected so that their induced e.m.fs. are adding. This is also the case for the j coils. Now, in order to adjust the compensating currents in the J coils the t and a coils are connected in opposition to the four j coils through a fluxmeter, and the current in the J coils so adjusted that the fluxmeter shows no residual deflection on reversing the primary currents. The value of H is determined as before. The t and a coils are then connected to the fluxmeter, and the fluxmeter readings give the mean induction in the M_1 and M_2 samples. It will be seen that this simplifies the testing by eliminating one adjustment.

Detailed Manipulation.—Normal Induction: In order to make the actual method of test clearer, the diagram of connections of Fig. 166 is given. This shows an arrangement of the Burrows permeameter in, perhaps, one of its simplest forms, suitable only for obtaining normal induction data by the precision method. Battery B_1 supplies current to the main magnetizing coil T, through the ammeter A_1 (which may be calibrated to read H directly), the regulating resistance R_1, and the reversing switch S_1. A similar parallel circuit R_2 S_2 (with or without an ammeter)

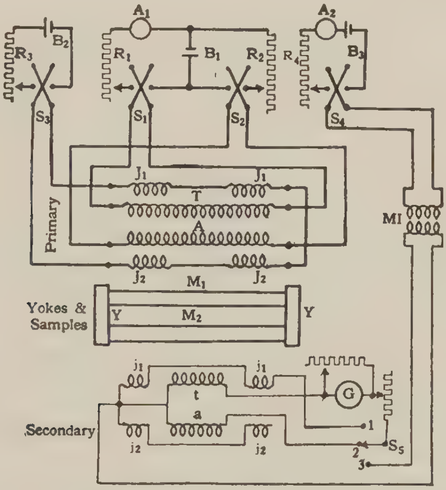

FIG. 166.—Magnetic and electrical circuits of the Burrows permeameter.

supplies the magnetizing coil A which surrounds the auxiliary sample. The compensating coils J are supplied from the battery B_2, through the resistance R_3 and reversing switch S_3. A mutual inductance MI is supplied from a third circuit consisting of battery B_3, resistance R_4, ammeter A_2, and reversing switch S_4. The exploring coils are so arranged that, with switch S_5 in position 2, coils t and a are connected in opposition through the fluxmeter G (equality adjustment); in position 1, coils t and j_1 j_1 are connection in opposition through the fluxmeter (uniformity adjustment); and in position 3, coil t is connected in series with the fluxmeter and the secondary of the mutual inductance (induction position).

With S_3 open, the specimens are demagnetized in the usual way by reversing switches S_1 and S_2 (which may be permanently tied together mechanically if desired), and gradually increasing resistances R_1 and R_2. The ammeter A_1 is then set for the lowest value of H desired, S_5 set on position 2, and R_2 adjusted until the fluxmeter shows no residual deflection when switches S_1 and S_2 are reversed simultaneously. This means that the test and auxiliary rods have the same flux density. S_5 is then thrown to position 1; S_1, S_2, and S_3 are reversed; and R_3 is adjusted until the fluxmeter shows no residual deflection, when the primary switches are reversed. This means that the flux in test sample M_1 is uniform. S_5 is then thrown back to position 2, and R_2 readjusted, if necessary. S_5 is then returned to position 1, and R_3 again adjusted, if necessary. Sometimes, these adjustments have to be repeated several times, since the two circuits have a mutual influence magnetically. When both adjustments are satisfactory, S_5 is thrown to position 3, and the fluxmeter deflection noted when the primary currents are reversed. This deflection is proportional to the induction B in the sample M_1.

Several methods of evaluating the induction may be used. In the first method the fluxmeter is calibrated by passing a known suitable current through the primary of the mutual inductance, as determined by A_2, and adjusting the fluxmeter series and parallel resistances until the fluxmeter has the required sensitivity. If it is desired that a 10-centimeter (or 10-division) deflection on the scale shall correspond to 10 kilogausses of induction, the current in A_2 should be:

$$I_B = \frac{N_2 A}{M_h 10^5}, \tag{73}$$

where I_B is the current through the primary of the mutual inductance;
A is the cross-section of the sample M_1 in cm².
N_2 is the number of turns in coil t;
M_h is the mutual inductance of MI in millihenries.

For other sensitivities, I_B is inversely proportional to the sensitivity.

A second method of evaluating the induction is to connect the secondary of the mutual inductance so that it gives a fluxmeter deflection in the opposite direction to that caused by the coil t; then, reverse S_1, S_2, S_3, and S_4 simultaneously; and adjust the current in A_2 until there is no residual fluxmeter deflection. Under these conditions,

$$B = \frac{M_h I_B 10^5}{N_2 A} = K_1 I_B. \tag{74}$$

In a third method a variable mutual inductance is used and its primary current through A_2 is kept constant If this current corresponds to full scale for ammeter A_2, a maximum accuracy may be obtained. Using the null method, as for the second type of test, when a balance has been obtained the induction is given as follows:

$$B = \frac{M_h I_B 10^5}{N_2 A} = K_2 M_h. \tag{75}$$

These last two methods have the advantage that the fluxmeter does not have to be calibrated. Also, a much higher fluxmeter sensitivity may be used, thus causing less strain on the eyes and greater reproducibility of results. By using a suitable variable mutual inductance, the last method is sometimes capable of giving a reproducibility of 0.1 per cent in meauring B for high inductions. If desired, a potentiometer may be used instead of the ammeter A_2, but, in general, the increased complication is not warranted.

Sometimes, especially if a ballistic galvanometer is used, instead of a fluxmeter, a semi-null method may have some advantages. In this case the third arrangement is used, but the mutual inductance is set to correspond to some even induction value near the true induction. The fluxmeter is calibrated to give, for instance, 10 centimeters or main divisions, for 1 kilogauss. On reversing the primary currents, the fluxmeter gives directly the amount to be added or subtracted from the even number of kilogausses.

In the case of the ballistic galvanometer, this method avoids the double kick and permits this instrument to give nearly as accurate results as the fluxmeter, unless the eddy-current lag is too great. The advantage of the semi-null method, if a fluxmeter is used, is that it gives the speed of a deflection method with the sensitivity of the null method. Obviously, with the straight null method, several reversals of the magnetizing current have to be made before a balance is obtained.

As pointed out by Burrows, if the main magnetizing current is caused to pass through the primary of the mutual inductance, when a balance is obtained the mutual inductance value is directly proportional to the permeability μ, since

$$B = M_h \times I \times \text{constant}, \tag{76}$$

$$H = I \times \text{constant}, \tag{77}$$

$$\text{therefore, } \mu = \frac{B}{H} = M_h \times \text{constant}. \tag{78}$$

In the case of the Burrows apparatus, as for all other ballistic methods, if there is an appreciable air space between the sample and the test coil t, a correction should be made at high inductions for the air flux, thus:

$$B_{\text{true}} = B_{\text{app}} - \left(\frac{a - A}{A}\right)H, \tag{79}$$

where B_{app} is the apparent induction;
B_{true} is the true induction;
a is the mean cross-sectional area of the coil t in cm.^{2};
A is the mean cross-sectional area of the sample in cm.^{2}

This will be further discussed later.

If laminated material or two bars cut from the same piece are to be tested, the American Society for Testing Materials method usually is to be preferred. In this case coils T and A are connected in series, through a single reversing switch, ammeter and regulating resistance; coils t and a are connected permanently in series; and the j coils are connected permanently in series. It will be noted that for the precision method, the j_2, j_2 coils were not used. In the American Society for Testing Materials method, they are required. A single instead of double compensating adjustment is now needed. With the t and a coils in series opposing the j coils, the current in the J coils is adjusted so that the fluxmeter shows no residual deflection. The procedure for measuring B is, then, as above, except that in this case N_2 equals the sum of the turns in coils t and a.

If desired, a single battery may be used instead of the three shown in Fig. 166. In order to reduce the necessary range of the ammeter A_1, it may be desirable to bring out a tap at the end of the first layer of coils T and A. By using the single layer coils, the ammeter A_1 will indicate 0.1 of the values of H for the same current as with the 10 layers. This means that the ammeter A_1 and the regulating resistances may have smaller ranges. By using suitable shunts with A_1, as many H ranges as desired may be obtained.

Hysteresis Loops.—In order to obtain hysteresis data, several methods are used, and it is here that the chief differences between the various types of Burrows permeameters appear. In Burrows' original apparatus a series of switches were arranged to introduce additional resistances in series with the various primary permeameter circuits, in order to reduce the currents; or, if desired, the currents in the A and J circuits could be increased by connecting the auxiliary resistances in parallel with the main resistances. This is the method used in the apparatus which is supplied by the Leeds & Northrup Co. In the apparatus as developed by the General Electric Co., the complicated switching devices necessary for the original Burrows method are eliminated to some extent by connecting all of the primary coils in series and adjusting the relative currents in them by shunting. In order to obtain hysteresis-loop data, additional primary windings are used similar to the original windings. These are connected in series with and opposing the main windings. By making the currents in the former greater than in the latter, reversed m.m.fs. may be obtained (see Fig. 167).[2] Magnetization curves are obtained by reversing a single reversing switch with the hysteresis switch closed. For hysteresis loops, the hysteresis switch is opened and the resistances shunting the J_2, A_2, and T_2 coils

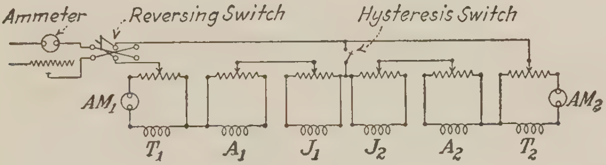

FIG. 167.

suitably adjusted. If the T_1 and T_2 coils have the same number of turns, H will be the difference in readings of AM_1 and AM_2. Obviously, for negative values of H, the readings of AM_2 must exceed those of AM_1. This arrangement has the advantage over the more common ones, of making the operation simpler. It has the disadvantage of requiring the reading of two ammeters instead of one for determining H, and of requiring much more complicated windings surrounding the test samples. The particular shunting arrangement not only serves the purpose of varying the currents in the coils, but is designed to keep the time constants of the various circuits independent of the settings.

The description of the circuits as used by the Bureau of Standards for the Burrows permeameter may be obtained from *Circular* 17 of the Bureau of Standards, or from the above-mentioned reference.[1] The Bureau no longer uses the mercury switches, but has adopted a special rocker gang-knife switch as supplied by the Leads & Northrup Co. The Burrows permeameter as built by the Leads & Northrup Co. is described partially in their catalog (*Bull.* 533). If it is desired to buy the apparatus complete, this equipment is undoubtedly satisfactory for most purposes.

Figure 168 shows the primary connections of the Burrows permeameter as used by the Research Department of the Westinghouse Electric and Mfg. Co., and Fig. 169 shows the secondary connections. This apparatus will be described in some detail in order to give an idea of the method of operation. It is a very complicated device when used for hysteresis data, but is complete and can be used for testing, either by the precision or the A.S.T.M. method, simply by throwing a few switches. Also, the circuits can be used for testing simple specimens, such as ring samples. A variable mutual inductance is provided, so that any one of the three above-described methods of measuring induction may be used. The apparatus is also arranged for testing material of any permeability from permanent-magnet steels to very high permeability samples. Both rod and sheet-metal yokes are provided. The latter take standard Epstein strips 3 centimeters (1$\frac{3}{16}$ inches) wide, and the average weight of sample is about 1 kilogram. Magnetizing forces up to 600 or 700 gilberts per centimeter may be attained by working rapidly to avoid undue heating. The apparatus is provided with a fluxmeter having a long scale distance of about 3 meters (10 feet). For simplicity, no parallel resistances are used in the primary circuits. All circuits are controlled by graded series resistances. For low currents, all of the resistances are in circuit. For the higher currents, the high resistances of low current-carrying capacity are short-circuited.

Referring to Fig. 168, the three batteries B_1, B_2, and B_3 supply current respectively to the main magnetizing windings 1 and 2, the compensating windings 3, and the primary of the mutual inductance M, through the line switches 1, 2, and 3. With the exception of 3, these do not need to be reversing switches. B_1 is ordinarily 30 volts, and B_2 and B_3 are 15 volts each. For high magnetizing forces, B_1 must be more than 30 volts. Switch 4 is a four-pole, double-throw, rocker switch which reverses the currents in the main windings 1 and 2. Rocker switch 5 reverses the current in the primary of the mutual inductance M, and rocker switch 6 reverses the current in the compensating windings. For normal induction data, these four switches are tied together by links. Switch 7 is a five-pole rocker switch which is used to

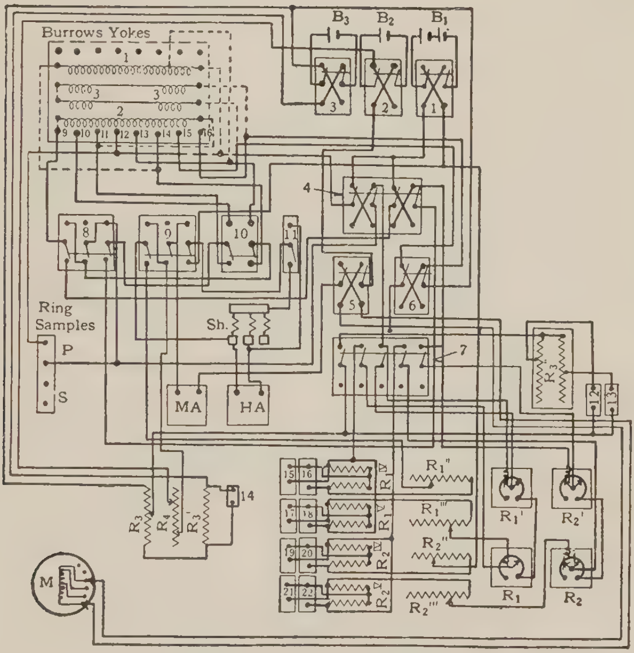

FIG. 168.

introduce resistance into the various circuits when obtaining hysteresis data. If desired switch 5 may be linked with switch 7. In this particular installation, switch 4 is operated by a foot lever, together with switches 5 and 6, if they are linked with it. Switch 7 is operated by another foot lever. This arrangement leaves the hands free to manipulate the secondary switches and to record the data. When switch 8 is up, coils 1 and 2 are in series for the American Society for Testing Materials method of test; and when it is down, the coils are in parallel through separate regulating resistances. The normal position for switch 9 is down; but when it is up, the ammeter *MA* and the shunt *Sh* are in series. With this latter connection, the two instruments *MA* and *HA* may be compared in order to detect readily any changes in calibration. Switch 10, when up, connects the circuits to one layer only, of coils 1 and 2; and when down, to 10 layers. Switch 11 changes the shunt *Sh* by a 10 to 1 ratio, depending on its position. For normal induction data with switch 7 up, resistances R_1, R_1' and R_1'' are in series and are used to adjust the current in coil 1. R_1 is a dial-resistance box having a resistance of about 1000 ohms; R_1' is similar, but with a resistance of about 100 ohms; and R_1'' is a slide resistance of about 5 ohms. It will be noted that R_1 and R_1' have two contacts. These are normally short-circuited by switch 7, but when this switch is thrown down, the resistances between these pairs of contacts are introduced, as is also slide resistance R_1'''. R_2, R_2', R_2'', and R_2''' similarly control the current in coil 2. If still lower currents are required, the switches 15 to 22 may be opened as needed, thus introducing 1000-ohm and 2000-ohm resistances in addition. These last are required only for material having very high permeability (in general a maximum μ of over 10,000). R_3 is a potentiometer arrangement for controlling the compensating current in coil 3. By this means, the compensating current may be reduced to zero if desired. R_3' is an additional resistance which may be introduced in series with R_3 by opening switch 14. R_3'' is a pair of resistances which are introduced into the compensating circuit when obtaining hysteresis data. Throwing switch 7 down automatically introduces one or the other resistance depending on which switch, 12 or 13, is closed. R_4 controls the mutual inductance primary current. For supplying current to ring samples, the magnetizing winding is connected to binding posts *P*, and switch 8 is opened.

Referring to Fig. 169 for the secondary connections, if it is desired to test according to the precision method, switch 28 is closed and switches 26 and 27 are opened. Switches 24 and 25 are closed to the left, putting in series opposing the main exploring coils 1 and 2, which surround the sample and auxiliary specimen respectively. This circuit is completed through the fluxmeter *G* with its regulating resistances, but not through the secondary of the mutual inductance. The residual fluxmeter deflection is brought to zero, when the primary currents are reversed, by adjusting the magnetizing currents in coils 1 and 2 (see Fig. 168). Switch 24 is then opened, and switch 23 is closed to the left. The compensating current is then adjusted for a fluxmeter balance, since coils 1 and 3 are connected in series opposing. These compensating adjustments are repeated until there is equality of flux between the two samples and uniformity of flux in the test sample. Switch 23 is then closed to the right, thus connecting coil 1 in series opposing the mutual inductance secondary. Switch 25 should also be thrown to the right, in order to reduce the fluxmeter sensitivity, but may be thrown back, if desired, for the final adjustment. For the null method of obtaining the induction, the primary of the mutual inductance is reversed simultaneously with the magnetizing currents by means

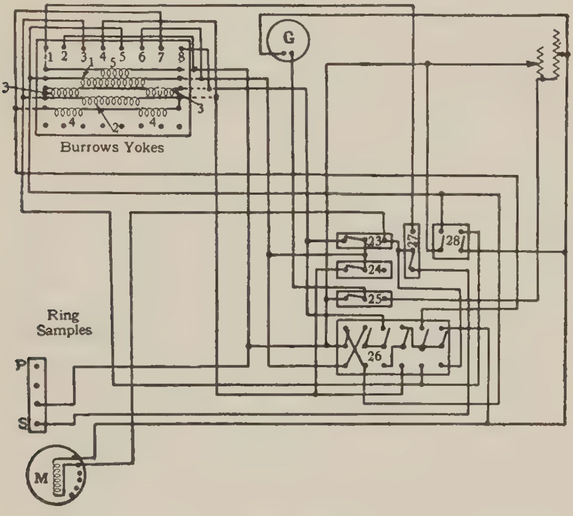

Fig. 169.

of the gang switches, and the variable mutual inductance varied until the fluxmeter indicates a balance. The induction is then determined by formula (75). This variable mutual inductance is similar to that described by Burrows in his original paper. It has primary taps for different ranges as indicated in Fig. 168. If desired, the fluxmeter may be calibrated to read B directly by the deflection method. In this case the calibration for the induction readings is made by reversing switch 5 by itself, with the secondary switches as indicated above. Switch 5 is then kept stationary when determining B. The secondary of the mutual inductance is automatically cut out of circuit when making the compensating adjustments, in order to increase the fluxmeter sensitivity (since the secondary of the mutual inductance has considerable resistance), and also for the purpose of eliminating the necessity of mechanically disconnecting switch 5 when making the compensating adjustments.

Coil 5 may be thrown into circuit for the deflection method, if desired, by closing switch 27 up and opening 28. This coil has much fewer turns than coil 1, and is wound on top of coil 1.

For the American Society for Testing Materials method of test, in which samples 1 and 2 are both tested, switches 23, 24, 27, and 28 are open. Switch 26 is closed up for compensation and down for obtaining B. In the up position of switch 26, coils 1 and 2 are in series opposing coils 3 and 4 through the fluxmeter and regulating resistances, but with the secondary of the mutual inductance open-circuited. With switch 26 down, coils 1 and 2, adding, are in series opposing the secondary of the mutual inductance through the fluxmeter. In this case a null or deflection method of obtaining B, as desired, may be used. Switch 25 is used as before for changing the sensitivity of the fluxmeter.

For ring samples, all secondary switches are open except 25 and 27, the latter being closed down. This puts the secondary of the ring sample in series opposing the mutual inductance through the fluxmeter.

Due to the different time constants of the various circuits, the fluxmeter, in general, is subjected to a double kick. With a critically-damped ballistic galvanometer, this is annoying and may cause appreciable errors. For this reason the variable mutual inductance was abandoned some years ago by the Bureau of Standards. When using a fluxmeter, however, this double kick is no longer a source of appreciable error. The variable mutual inductance has been retained by the Westinghouse Co., both for experimental and commercial magnetic testing, due chiefly to its advantages when testing large numbers of samples of sheet material. As explained above, the mutual inductance is set to a value corresponding to the weight of the sample and the required induction. This gives a ready means of adjusting for the weight of sample, makes possible the use of a high fluxmeter sensitivity and avoids the necessity for frequent fluxmeter calibration. When magnetizing forces corresponding to one or two, or, at most, three inductions, are required, this is a very satisfactory procedure. As will be explained later, a second mutual inductance is used when obtaining high-induction data for the purpose of automatically correcting for air leakage between the sample and test coils. This is used only when the 10-layer coils are employed. For the commercial testing of permeability, a much simpler apparatus is used, but the principle is the same. While this apparatus is complicated, yet a new man can be taught in an hour to obtain normal-induction data and in a day or two he can obtain satisfactory hysteresis data. It takes some weeks of practice, however, before hysteresis data can be determined with any reasonable speed.

There are only two features of the Burrows apparatus which may cause real difficulty, assuming that the switches and connections are in satisfactory condition. In the case of the precision test, if the samples are somewhat different, the compensating current, sometimes may have to be reversed from its normal direction over certain ranges of induction. The other difficulty is that for certain small negative values of H, when obtaining hysteresis data, switch 6 sometimes must not be reversed when the other primary switches are operated. By the link system used, this switch may readily be detached, when desired, in order to permit this type of operation.

The magnetic circuit for laminated material is shown by Fig. 170. A link sample is shown in this sketch, the purpose of which will be discussed later. These yokes are designed primarily to take Epstein strips which are 50 by 3 centimeters ($19^{11}/_{16}$ by $1^{3}/_{16}$ inches). The flux passes into the yokes through the edges of the strips rather than through the sides, thus tending to make the reluctance of the magnetic paths for all of the strips of a sample nearly alike. The yokes are made of laminated material, thus tending to reduce the eddy-currents and make the testing easier and more reliable. The secondary windings are placed on micarta tubes having inside dimensions of about 3.18 by 0.95 centimeters (1¼ by ⅜ inch). Outside of them are other micarta tubes which are grooved on a lathe with 16 turns per inch, and take the primary windings. The primary and secondary coils are easily removable from the yokes and from each other, thus facilitating repairs if such ever should be necessary. No. 30 d.c.c. magnet wire is used for the secondary windings, and No. 18 d.c.c. magnet wire for the primary coils. With 16 turns per inch $H = 7.92I$ for the single-layer winding. In order to make H direct reading, special millivoltmeter shunts are provided. If desired, of course, more turns per inch could be used, making $H = 10I$. This would require a smaller wire or some special winding arrangements.

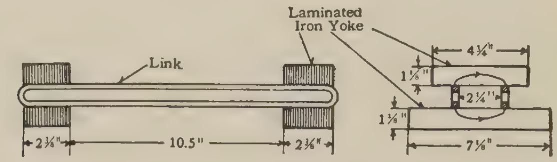

Fig. 170.—Magnetic circuit of Burrows permeameter for bars and laminated specimens.

In connection with the Burrows permeameter, a few details are important with respect to the testing manipulation. To some extent with solid samples, especially if they have high maximum permeability, and to a considerable extent for laminated material, the method of clamping in the yokes may affect the permeability determinations in the region of low and medium inductions. Clamping strains may easily reduce the maximum permeabilities 20 per cent or more. For this reason, samples should be clamped loosely. The method of clamping laminated material on the edges is of particular advantage in this respect, since strips of sheet material are usually more or less bent, as received, and, if they are allowed to stand on edge with the laminations packed very loosely, bending strains need not amount to much; whereas, if they are clamped on the sides, their permeability may be decreased by a considerable amount.

In the process of obtaining normal-induction data in the region of maximum permeability, the adjustment of the compensating current is of the utmost importance, especially for high-permeability material. This is also true when obtaining hysteresis values in the region of low inductions, such as coercive-force determinations. When obtaining values of H for definite values of B, the induction readings must be very accurately determined for high inductions, since the normal-induction curve is so flat. For instance, at $B = 16$ kilogausses, an error of 1 per cent in determining the induction for electrical sheet will mean a 10 to 14 per cent error in magnetizing force and hence in permeability. For high inductions, the adjustment of the compensating current does not have to be particularly accurate.

In order to obtain reliable results with the Burrows permeameter, it is particularly important that the samples be magnetically uniform throughout their length. If this is not the case, very large errors may occur for high-permeability material, as will be discussed in some detail later. Commerical sheet is usually sufficiently uniform that there is no trouble with the testing from this standpoint.

Fahy Simplex Permeameter.—This permeameter is, perhaps, the simplest in construction and the simplest to operate of any of the commercial permeameters using the ballistic method. Except, perhaps, for very uniform samples, its accuracy is equal to or better than that of the Burrows permeameter, and the speed of operation is considerably higher, especially for hysteresis data. It is used by the Bureau of Standards in preference to the Burrows for much of their testing. The general appearance of the yokes

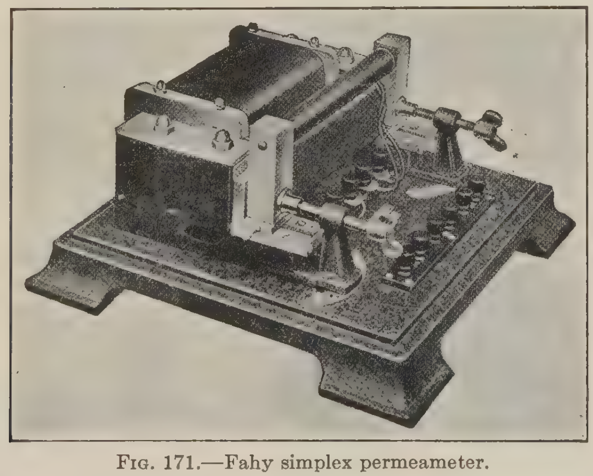

FIG. 171.—Fahy simplex permeameter.

and coils is shown by Fig. 171. Figure 172 shows the magnetic circuit in plan and elevation. The yoke Y is made of high-grade laminated steel in order to reduce the eddy-currents and residual induction. The center leg of the yoke is supplied with a magnetizing winding M capable of giving an H of 200 gilberts per centimeter for a magnetizing current of the order of 2 amperes. The sample is located at X, as shown by the dotted lines, and is surrounded by a test coil T of 100 turns. This sample may have any cross-section up to 0.75 by 1.75 inches (1.91 by 4.45 centimeters). Two iron posts PP are clamped against the sample and carry between them the air coil H, consisting of several thousand turns of fine wire. When coil T is connected to a ballistic galvanometer and the current in M is reversed, the galvanometer deflection will give the induction. The galvanometer may be made direct-reading, as for the simple ring test previously described, by suitable calibration with a mutual inductance. Formula (73) may be used for calculating the mutual inductance primary current. If the galvanometer is next connected to coil H, the magnetizing force may similarly be determined from the galvanometer deflections when the current in M is reversed. In this case, also, the galvanometer may be made direct-reading. The method of obtaining H is the magnetic-potential-coil method d described in Chap. XV. If the sample X consists of laminations, the iron posts P, as explained by Fahy, serve to draw the flux from the yoke through the sample and give substantially the same flux in all of the laminations. The true H values are not quite those corresponding to the area turns of the coil H. The constant for this coil is determined by calibration, using a sample of known magnetic characteristics in place of X.

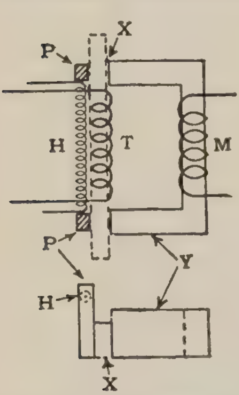

Fig. 172.—Connections of the Fahy Simplex permeameter.

For hysteresis data, the procedure is similar to that for ring samples. After obtaining the tip value, resistance is inserted, by a suitable switch, into the M circuit, and the corresponding ΔB is measured by the ballistic galvanometer. A return is then made through the suitable sequence to the tip value of the loop, and ΔH determined. B is obtained by subtracting ΔB from the tip value B_m, and H by subtracting ΔH from H_m. If only approximately correct results are required, H may be obtained by opening the M circuit after the ΔB deflection, and noting the deflection with the galvanometer connected to the H coil. This gives H directly, if there is no appreciable residual in the yokes.

The apparatus is supplied with a suitable control box very conveniently arranged. It contains a multiple-range ammeter for calibrating the fluxmeter, a mutual inductance, the necessary switches and galvanometer calibrating resistances. The current-control resistances are external. This apparatus is supplied with special adapting blocks of soft iron, if desired, so that round rods of any reasonable size up to 0.75-inch (1.9-centimeters) diameter may be tested.

This apparatus is extremely simple, easy to operate, and gives reproducible results. It has one disadvantage over the Burrows in that definite values of H have to be obtained by a cut-and-try method or by plotting a curve. On the other hand, it has the very decided advantage that nonuniform samples probably can be tested more correctly by means of the Simplex than by the Burrows; namely, more nearly mean values will be obtained with the Simplex. Further comparisons will be made in a later chapter.

Comparison Methods.—When it is desired to test a large number of samples having similar properties, it is often convenient to have a standard sample which has been calibrated by some absolute method, and then use some simple comparison test. If the same magnetomotive force is applied to the two samples (the standard and the unknown) and the corresponding induction in each is measured, the m.m.f. is known from the calibration of the standard sample, thus making it unnecessary to measure H directly. This is often an advantage, because H is much more difficult to measure accurately than is B. A number of methods have been devised for taking advantage of this fact.

Burrows Permeameter as Comparison Instrument.—Referring to Fig. 166, if desired, an ammeter may be placed in series with the main magnetizing winding of the auxiliary sample, as well as in series with the magnetizing winding of the test sample. After completing the compensating adjustments, if the auxiliary rod already has been standardized, it is not necessary to measure the induction in either sample, since both have the same induction; therefore, from the known B-H curve of the auxiliary rod and the observed m.m.f., the induction of the unknown sample may be deduced. This is the inverse of the method described in the preceding paragraph. If desired, the ordinary procedures for the Burrows test may be followed and the known properties of the auxiliary rod used simply as a check on the accuracy of the tests. This method may be inaccurate if the joint reluctances or if the two samples are much different, since the compensation for uniformity is correct for only one of the samples.

Fahy Duplex Permeameter.—In addition to his Simplex permeameter, Fahy has developed a duplex instrument which may be used for comparing a standard sample having known magnetic properties with an unknown sample having approximately the same dimensions. This apparatus uses the ballistic method of test. A complete decription of the Duplex instrument is given in a Bureau of Standards publication.[3] In addition to being used as a comparison instrument, the Duplex is capable of testing single samples by what is known as the absolute method. The principle of operation is similar to that of the Simplex, but the manipulation is somewhat more complicated. Figure 173 shows the essentials of the Duplex apparatus, together with the internal connections. The magnetic yoke is in the form of an *H* with a standard sample *A* and the unknown *X* placed as shown by the dotted lines. The magnetizing coil *M* sends flux around the two circuits of the permeameter through the samples, as indicated by the arrows. In general, due to differences in the samples, these fluxes will be different. In order to make the magnetic potentials for the two samples equal, the two secondary coils *T*, *D*, *D′*, and *S*, all having the same number of turns, are connected in series with a ballistic galvanometer so that the induced

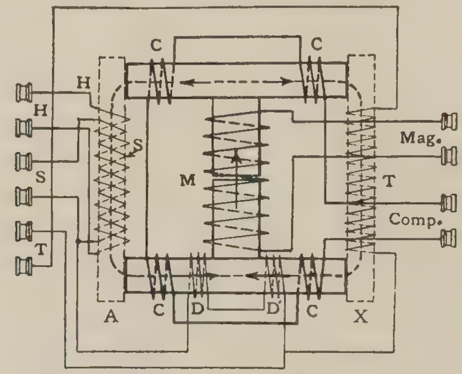

FIG. 173.—Electrical connections of the Fahy Duplex permeameter.

e.m.fs. in coils S and D' are in the same direction, but opposite to that generated in T and D. The compensating coils C are supplied from the same battery as M, but through separate reversing switches and control resistances. If, now, the currents in M and C are reversed simultaneously, and the compensating current adjusted so that there is no residual deflection of the galvanometer, the leakage fluxes for the two magnetic circuits of the permeameter will be balanced and the same magnetizing force will be applied to the samples. Then by connecting T and S successively to the ballistic galvanometer, which is calibrated in the usual way with a mutual inductance, the values of B for the two samples may be read. From the known B-H curve for the standard sample, H is known for the X sample.

In order to test a single bar by the absolute method, the sample is placed in T. The procedure is the same as for the comparison test, except that the magnetizing force is read by connecting the air coil H to the ballistic galvanometer. This coil has a large number of turns, and measures the difference in magnetic potential between the yokes, or, when the apparatus is compensated, gives the value of H as applied to the sample X in coil T. The principle will be evident from the previous description of the Simplex instrument. In order to alter the time constant of the magnetizing circuit, there is a variable air-gap located at M. If a fluxmeter is used as a detector, this is unnecessary.

Van Lonkhuyzen Method.[4]—This simple but not very accurate method may make use of ordinary Epstein samples (see Chap. XX) if desired, the magnetization curve of one of which is known. Referring to Fig. 174, the standard sample is N and the unknown is X. These samples each preferably consist of four bundles of strips arranged in a hollow square, as for the Epstein test. This allows the magnetic circuit to be completed, and thus keeps the flux more uniform. M_n and M_x are the respective magnetizing coils which surround the samples, and S_n and S_x are corresponding secondary coils also surrounding the samples. W_n and W_x are variable resistances of such a magnitude that the resistances of the coils S_n and S_x are negligible. G is a ballistic galvanometer or fluxmeter. Magnetizing current is supplied from the battery B through the resistance R, ammeter A, and reversing switch K. If a comparison is desired at a certain m.m.f., R is adjusted until the ammeter A indicates this value. The corresponding induction in the standard sample N is known from a previous calibration. W_n, which is marked in terms of induction in sample N, is set to this induction; K is then reversed and W_x adjusted until G shows no residual deflection after this reversal. The reading of W_x then, gives the induction in sample X. The m.m.f. for X is known from the reading of the ammeter, since M_n and M_x are in series.

This method is probably reasonably reliable for inductions above 14 kilogausses, but for lower inductions should be subject to considerable errors due to variations in the gap reluctances.

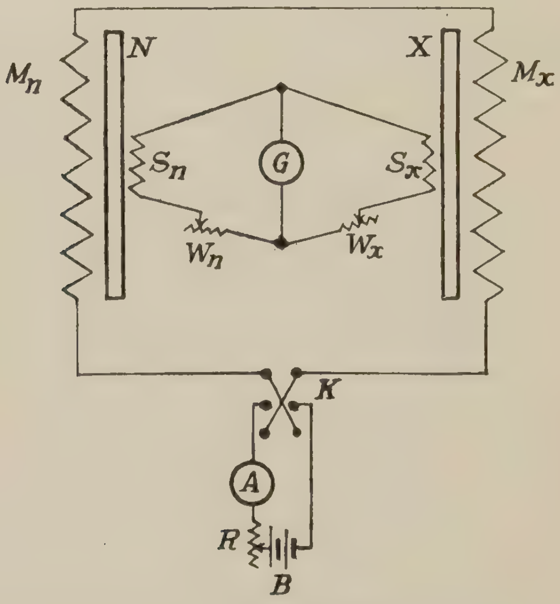

FIG. 174.—Van Lonkhuyzen differential permeameter.

At inductions of about 10 kilogausses, the reluctance of the joints may be two or three times the reluctance of the sample for buttjoints and a considerable percentage even for alternate buttjoints and lapjoints. For inductions of 16 kilogausses or more, the joint reluctances are relatively unimportant. Due to its simplicity, this method should be fairly useful for comparison tests on similar materials at high inductions. If means are provided for compensating for joint reluctance, the accuracy of the method could be greatly increased. It should be possible even to apply it to single straight samples.

Ewing Permeability Bridge.—As for most comparison methods, the principles of operation and manipulation are quite simple for this well-known permeability bridge.[5] Two samples, a standard and an unknown, are connected at the ends by short yokes. A magnetizing coil surrounds each specimen. The turns on the standard sample are such that 1 ampere corresponds to 10 gilberts per centimeter. The turns on the unknown sample are adjusted by means of dial switches. Arrangements are provided for keeping the resistance constant as the turns are changed. An inverted U-shaped piece of iron is arranged with its ends in contact with the yokes, so that, if there is a difference of potential between the yokes, flux will pass through the U piece. At the center of the U is an air-gap containing a compass needle. Now, if the flux in the two test bars is not equal, a difference of m.m.f. will exist between the yokes, and the compass needle will deflect. This deflection may be brought to zero by adjusting the turns on the unknown sample, when the flux in the two bars will be equal. On account of hysteresis effects, the magnetizing currents should be repeatedly reversed during this adjustment. From a knowledge of the *B-H* curve of the standard bar, which has been calibrated by some absolute method; of the m.m.f. applied to the standard sample, as determined by an ammeter in series with the magnetizing winding; and of the relative turns on the two bars, the m.m.f. for the unknown bar may be calculated. In spite of its simplicity, this apparatus is no longer used to any extent, due to certain inaccuracies caused by variable joint reluctances and other more or less indeterminate factors.

Barbagelata Permeameter.—A rather novel permeameter[6] making use of a null method with the aid of a condenser is shown by Fig. 175. The chief object of this method is to compensate for the magnetic lag in the test sample due to eddy-currents, which is often of considerable magnitude, especially when testing samples of low-resistance solid material. For this type of sample, when using a null method and standard mutual inductance, the double kick in the galvanometer may be very annoying. This condenser method is applicable to any permeameter which measures induction by means of the ballistic method.

N_1, the magnetizing winding on the sample, is in series with a resistance R_1 and a reversing switch S. The magnetizing current is supplied in the usual way from a battery through a regulating resistance and ammeter. The secondary winding N_2 on the sample is in series with the ballistic galvanometer G and the variable resistance r. A variable voltage is applied to the condenser circuit, its value depending on the resistance R_1 and the primary current applied to the sample. Its value is read by the voltmeter V. Now, obviously, when S is reversed, the condenser, which is charged to the voltage V, will be discharged and charged again in the reverse direction to the same voltage. The discharge and charging currents will produce a voltage drop in r, which is opposed to the voltage generated in the coil N_2 caused by the reversal of flux in the sample. By properly adjusting r, the residual deflection of G may be made zero. Under these conditions,

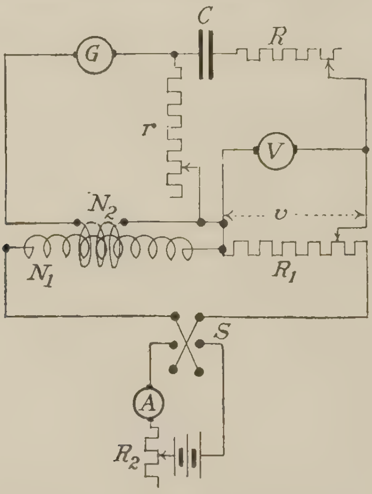

FIG. 175.—Barbagelata permeameter.

$$B = 100\frac{Cvr}{N_2A}, \tag{80}$$

where B is the induction in gausses;

C is the capacity of the condenser in microfarads;

v is the voltage applied to the condenser circuit;

r is the value of the resistance r in ohms;

N_2 is the number of turns in the sample secondary winding;

A is the cross-section of the sample in square centimeters.

If r is adjusted, so that

$$r = 10\frac{N_2A}{C};$$

then,

$$B = 1000v. \tag{81}$$

Thus, B is directly proportional to the reading of the voltmeter V, and the voltmeter may be calibrated directly in terms of gausses.

The function of the variable resistance R is as follows: Due to the time constant of the primary circuit, there is a lag in the applied m.m.f. after reversing the switch S. This may be made small by using a high voltage and large value of the resistance R_2. When testing, there is another lag in the building up of the flux, due to the eddy-currents induced in the sample. This may amount to many seconds for samples of low resistance and large cross-section. By increasing the value of R, the time of discharge and charge of the condenser may be prolonged according to the well-known condenser laws. In this way the total time of the flux change and of the flow of current in the condenser circuit may be made approximately equal, thus resulting in much smaller galvanometer deflections than would otherwise be the case. The rates of change in the two circuits cannot be made the same for all portions of the interval, but may be made sufficiently alike so that the accuracy of testing is considerably improved when using a ballistic galvanometer. With a fluxmeter, there is probably little advantage in the use of the method.

Bureau of Standards Short-bar Permeameter.—It is sometimes of considerable advantage to be able to measure the magnetic properties of small samples. The Bureau of Standards has developed a device[7] shown by Fig. 176 which will measure sam-

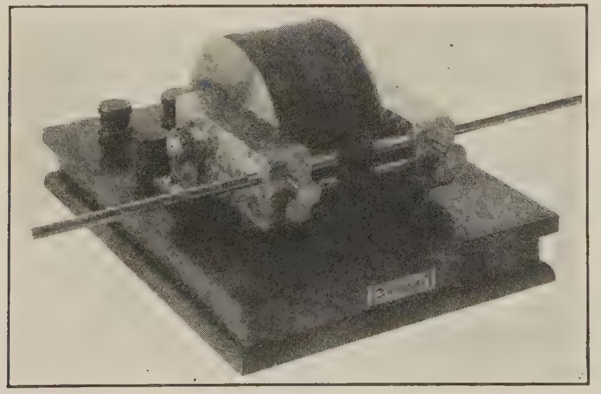

Fig. 176.—Bureau of Standards magnetic comparator for short bars.

ples 10 centimeters long and 0.6 centimeter in diameter. This is a much shorter sample than can be used in most commercial permeameters.

The reference sample (long bar at the top) and the test sample (10-centimeter bar at the bottom) are inserted in the yokes as shown. Each bar is surrounded by an exploring coil. These coils may be connected successively to a ballistic galvanometer. Magnetizing current sufficient to give the desired induction in the test bar is reversed, and the inductions in the two bars obtained from the galvanometer deflections. From the observed induction in the reference bar, the corresponding H value may be deduced from its known calibration curve, which has previously been determined by means of a standard permeameter. Due to magnetic leakage and other effects, the actual H value for the test sample will vary by a small amount, depending on the magnetic quality of the test bar. Simple methods of correction have been devised making use of so-called selector curves, as described in the original paper. Ingenious methods are also shown for obtaining hysteresis data by comparison with various reference bars. An accuracy of 5 per cent in H is claimed for this apparatus. H values as high as 1000 gilberts per centimeter may be readily obtained.

High-induction Tests.—The ordinary permeameter, due to limitations in the magnetizing windings and the switching devices, is usually not adapted for magnetizing forces above 300 gilberts per centimeter, though in some cases this value may be considerably exceeded for short periods, provided the windings are given time to cool between tests. In order to determine the characteristics of polepiece material for electromagnets, material to be used in the teeth of rotating machines, some of the cobalt permanent-magnet steels, and for a determination of the saturation values of materials for scientific purposes, it is necessary to go to much higher m.m.fs. In general, this means a radically different type of permeameter from those already described, and so arranged that the field of an ordinary electromagnet may be highly concentrated, thus giving an augmented m.m.f. over a short distance.

Isthmus Methods.—An isthmus method, together with actual test results, has been described quite completely by Ewing.[8] A powerful electromagnet is used to start with, and the field is further concentrated by the cone arrangement shown in Fig. 177.

The specimen is turned down, forming two cones with a small cylindrical isthmus between. The smaller the isthmus the greater the concentration of flux. In a preferred form of apparatus the polepieces have a cylindrical opening in which the sample may be revolved. Surrounding and close to the isthmus is an exploring coil. Concentric with this coil is another having a little larger diameter.

The operation is as follows: The inner exploring coil is connected to a ballistic galvanometer and the bobbin or sample revolved 180 degrees. The resulting galvanometer deflection is proportional to the flux in the isthmus, just as the case would be if the magnetizing current were reversed. This procedure is used instead of reversing the current, since in the latter case the large inductance and current would make the switching difficult and there would be a large time lag in the flux change unless laminated poles and yokes were used. Next, the inner and outer exploring coils are connected differentially through the galvanometer and the sample again revolved 180 degrees. From the galvanometer deflection and the cross-sectional area between the two exploring coils, the value of H can be calculated. As obtained by this method, Ewing reports magnetizing forces as high as 24,500 gilberts per centimeter and inductions of about 45,000. By making the isthmus portion of the sample sufficiently short and prop-

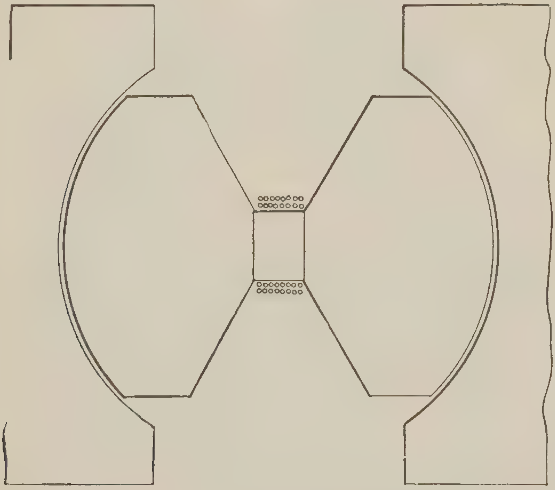

FIG. 177.—Ewing isthmus method.

erly sloping the sides of the cones, approximately uniform flux may be produced in the isthmus. If the cone arrangement were not used, the flux would be far from uniform in the sample. As pointed out by Ewing, the slope of the cones for the maximum concentration of flux is not the same as for the most uniform field. In the former case, assuming saturated polepieces, the angle between the cone sides and the axis should be theoretically 54 degrees 44 minutes, or in practice about 60 degrees. For the most uniform field, the angle should be 39 degrees 14 minutes. Actually, a compromise generally would be used.

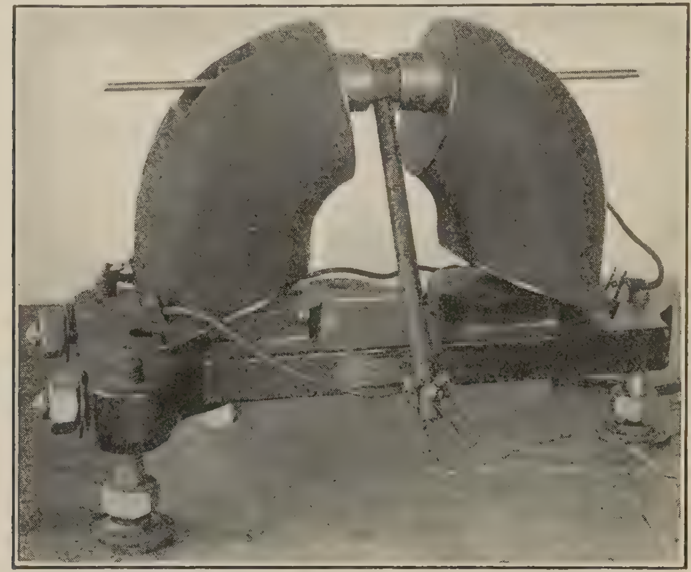

Fig. 178.—Bureau of Standards high magnetization tester.

For use with this method, the samples are rather difficult to prepare, the manipulation is not easy, and the determination of the area of the test coils requires considerable care. When less intense fields will suffice, other more convenient methods are now generally used. Several modifications of the isthmus method have been devised. A number of them are described in Glazebrook's "Dictionary of Applied Physics," Vol. II.

Bureau of Standards Method.—The Bureau of Standards method[9] for obtaining high-induction data is very similar to that previously devised by Campbell and Dye.[10] It is capable of giving results up to several thousand gilberts per centimeter.

Figure 178 is taken from a photograph of the apparatus. Between the poles of a Du Bois electromagnet, two cylindrical extension pieces are arranged with an air-gap of about 2 centimeters between them, and drilled so as to take a rod 6 millimeters in diameter. The length of the sample is immaterial, provided it is long enough to give good magnetic contact with the polepieces. Surrounding the sample are three concentric coils of No. 40 (B & S gage) enameled magnet wire, each having 100 turns and the respective diameters of 7 millimeters, 10 millimeters, and 13.2 millimeters. The mean cross-section of such coils may be most conveniently determined by calibrating ballistically in a standard solenoid by the usual methods.

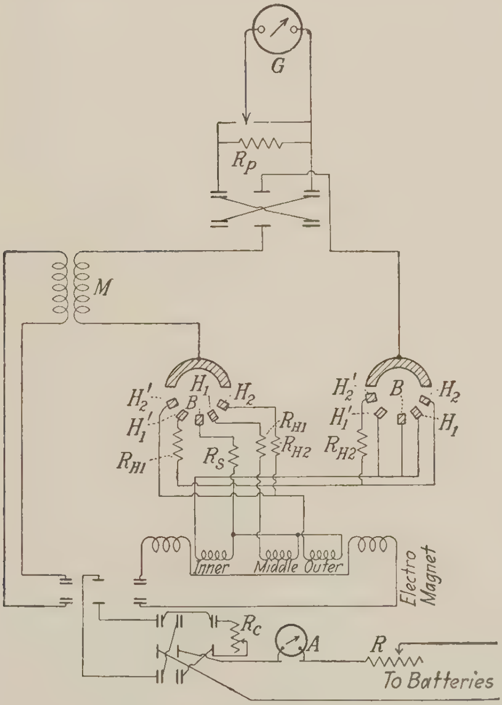

Fig. 179.—Diagram of connections of Bureau of Standards high magnetization tester.

The diagram of connections is given by Fig. 179. *B* is measured by connecting the inside coil to a ballistic galvanometer and reversing the magnetizing current. *H* is determined by connecting the two inside coils in series opposing to the ballistic galvanometer, noting the deflection when the magnetizing force is reversed and then doing the same with the outside pair. The gradient of the magnetizing force then can be determined and extrapolated to the surface of the sample. The hysteresis data may be obtained by a procedure similar to that used for the Fahy Simplex permeameter.

It was found by the Bureau of Standards to be rather difficult to obtain correct coercive-force data, due to the magnetic viscosity and retentivity of the yokes, and possibly to other causes. By a modification of the usual procedure, however, this difficulty was overcome. If the induction apparently is reduced to zero, the actual induction is probably some other value, due to the above-mentioned effects. The procedure adopted is to bring B approximately to zero by introducing resistance into the magnetizing circuit and reversing the magnetizing current so that, apparently, $\Delta B = B_m$. Then, the induction is rapidly increased to $-B_m$ and back to B_o. In general, the galvanometer will indicate a residual deflection. By repeating the procedure and varying the added resistance in the magnetizing circuit, this residual deflection may be reduced to zero. After the final adjustment, by repeating the procedure with the H coils connected to the galvanometer, the resulting deflection will be $2H_c$. By comparison with tests on the same samples with other types of apparatus, this procedure was found to give correct results. The chief advantage of the Bureau of Standards method over the original Ewing isthmus method is that the former uses simple cylindrical samples instead of the complicated bobbin specimens. For magnetizing forces up to several thousand gilberts per centimeter it should be quite satisfactory.

Other High-induction Methods.—For testing rectangular bars at high inductions, H is often measured by means of thin wide rectangular coils of fine wire placed adjacent to the sides of the bars near the middle, with their axes parallel to the direction of the magnetic flux (see Fig. 180). If the coils are thin enough and close enough to the surface of the samples, H values will be given quite accurately when the flux is reversed and the coils are connected to a ballistic galvanometer. If desired, such an H coil may be rotated 180 degrees around an axis at right angles to the axis of the sample, in order to give the galvanometer deflection. The "Dictionary of Applied Physics" gives several modifications of this method. Obviously, this method can be used only for fairly high values of H, unless an extremely sensitive galvanometer is available, since the coils must be thin and therefore must have a small cross-section.

Fahy has recently devised an attachment for his Simplex permeameter which makes possible the high-induction testing of short samples without increasing the current in the field coils beyond its normal maximum value. The principle of operation is the same as for the ordinary Simplex, but the total m.m.f. is concentrated on a short length of specimen. This high-induction adapter may be used, not only with the magnetizing yokes of the Simplex permeameter, but, if desired, with any other convenient source of magnetomotive force which may readily be reversed in polarity, such as an ordinary U-shaped electromagnet. The adapter is shown in Fig. 181. When used with the Simplex permeameter, the standard B coil and the H coil, with its extension blocks, are removed. The adapter itself consists of two

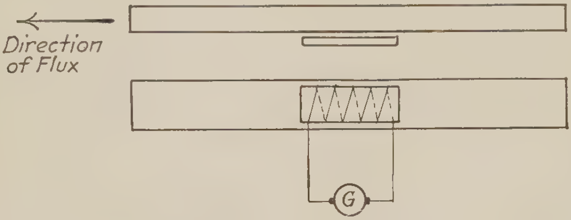

FIG. 180.—Method of measuring H at high inductions.

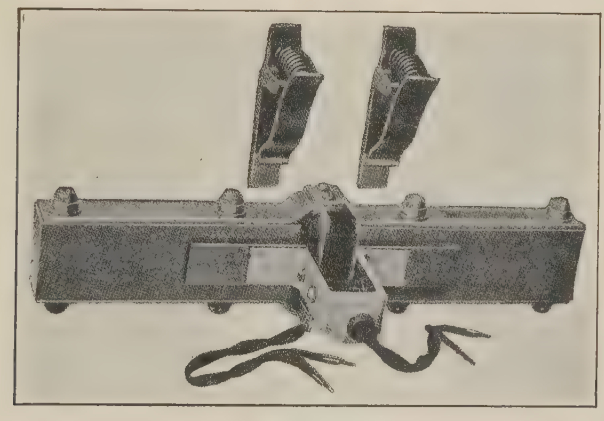

FIG. 181.—Fahy high magnetization adapter.

laminated bars, separated by a gap, which are placed against the face of the Simplex yokes in place of the usual sample. Across the gap between the adapter bars is placed the sample to be tested. This sample may be quite short, if desired, thus requiring a small amount of material. Surrounding the sample is an exploring coil for measuring B, as for the standard Simplex. Against the face of the sample are two thin magnetic extension blocks between which is the H coil, the construction being similar to that for the regular Simplex permeameter. Two clamps hold the sample and coils in position. The exploring coils are readily connected by means of flexible leads to the Simplex binding posts.

The method of operation is exactly the same as for the Fahy Simplex permeameter. Both normal-induction and hysteresis data may be obtained. The device is suitable for m.m.fs. well over 1000 gilberts per centimeter, and is said to be reasonably accurate down to 10 gilberts per centimeter. By means of this adapter, data may be easily obtained for extrapolating, for the purpose of obtaining saturation inductions. Also, such material as the high-cobalt magnet steels may be tested up to the required high magnetizing forces.

A method of obtaining very high currents for a very short interval of time, and therefore very high magnetizing forces, has recently been developed by Kapitza.[11] It consists simply in using a lead storage battery composed of new plates which have been only slightly formed, and which are placed close together. Under this condition, enormously high instantaneous currents may be obtained through a low-resistance coil. On short-circuit, currents as high as 13,000 to 14,000 amperes have been obtained. For the most efficient output, a 7000-ampere current has been used. A power output of about 1000 kilowatts has been obtained. With a coil 1 millimeter in internal diameter, a flux density of 500 kilogausses for 0.003 second has been produced. Kapitza estimates that two or three million gausses are possible by this method. For making the circuit special copper-leaf switches were developed and special fuses were used for breaking the circuit. This is obviously not a commercial method of testing the magnetic properties of materials, but should be extremely valuable for scientific work connected with the investigation of magnetic phenomena at high inductions.

Testing Nonmagnetic Steels.—When a sample has a permeability of about one, the ordinary permeameter test is usually not sufficiently accurate, due to the fact that the air correction then becomes practically as large as the value which is to be measured. If, however, the required magnetizing force is applied to the permeameter with no sample in position, the flux through the exploring coil measured, then the sample introduced and another flux measurement taken, fairly reliable results may be obtained, especially if a null method and long-range mutual inductance is employed.

Since a nearly nonmagnetic sample in the form of a rod or bar has practically no demagnetizing effect, the arrangement shown in Fig. 182 may be used.[12] N_1 is a solenoid; N_2 is an exploring coil in which the sample is placed; MI is a variable mutual inductance, and G is a galvanometer or fluxmeter. With no sample in the coil, MI is adjusted for no galvanometer deflection on reversing the current. With the sample in position, the galvanometer deflection may be noted when the current is reversed, or MI may be adjusted for zero galvanometer deflection. The permeability is readily calculated in the ordinary way; first, by dividing the indicated extra flux by the cross-section of the sample, which gives the ferric induction B_f; then,

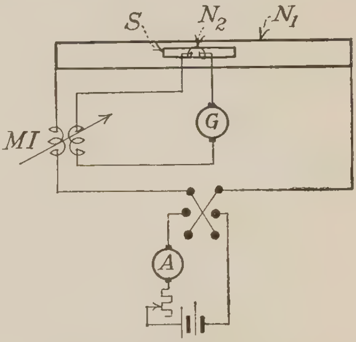

FIG. 182.—Permeability test for feebly magnetic material.

$$\mu = \frac{B_f + H}{H}. \tag{82}$$

H is given by the number of turns per centimeter and the current (see formula (72)).

Testing Permanent-magnet Steels.—Any of the ordinary permeameters may be used for testing permanent-magnet steels with the exception of the high coercive-force cobalt steels. These require some form of high-induction apparatus, since a maximum m.m.f. of the order of 1000 gilberts per centimeter is necessary. The requirements of a permeameter for permanent-magnet steels are not so severe, in general, as for ordinary materials, due to the fact that the permeabilities are low and the coercive forces high; therefore, leakage and joint reluctance do not cause so much difficulty.

If the material is to be tested in the form of completed magnets, the ordinary permeameter of course, cannot be used. If the magnets are for d.-c. indicating instruments, magnetos, or similar applications, one of the simplest methods is to use a d.-c. ammeter movement of the moving-coil type, through which is passed a definited d.c. If the magnet to be tested is inserted in place of the ordinary instrument magnet, the readings of the pointer attached to the moving coil will be proportional to the strength of the magnet. If further data, such as coercive force, retentivity, etc., are required the magnet under test may be provided with a magnetizing winding. The test procedure is obvious. In using such a test, one thing should be remembered: If the magnet is magnetized before inserting in the tester, a certain property of displaced hysteresis loops, as described in a previous chapter, comes into play, provided the tester is supplied with polepieces. Referring to Fig. 183, after the magnet has been magnetized to B_m by the m.m.f., H_m and the applied m.m.f. is removed, due to the demagnetizing effect of the air-gap, the flux will be reduced to a point such as a instead of B_r, as would be the case with no air-gap. When the magnet is placed in the tester, the demagnetizing effect is reduced due to the shortening of the effective gap by the polepieces. The flux then rises slightly to b. Now, if a demagnetizing force is applied to the magnet, the flux will take the upper path of a small displaced loop to a, and then will follow the ordinary hysteresis loop to H_c. The path a-b is a function not only of the nature of the magnetic material, but of the relative gap dimensions of the magnet and tester.

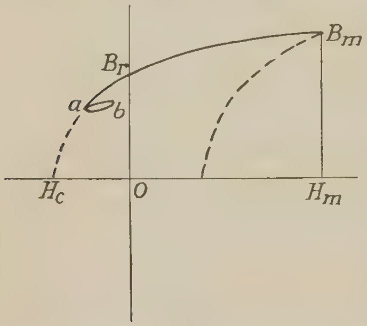

Fig. 183.—Hysteresis loops showing effect of varying demagnetization.

In some testers, instead of using a moving coil, a rotating armature is employed. As a modification of this, Watson describes an instrument which uses a rotating iron disk with one brush on the shaft and another on the periphery. The arrangement is a sort of homopolar generator. The periphery of the disk and the shaft are of brass. This is a modification of an apparatus devised by Betteridge.[13] The disk is placed between suitable polepieces and is rotated at a uniform speed. The field is produced by the magnet which is to be tested. The specimen is supplied with a magnetizing winding and the magnetizing force H is given by an ammeter in series with this winding. The induction B is given as a function of the voltage generated in the disk, as read by a millivoltmeter. By suitable compensating shunts, the air-gap and joint reluctances may be compensated for, and B or B_f may be read as desired.

For watt-hour meter magnets one of the most obvious tests is by the use of a watt-hour meter to which is applied a known current and voltage. If desired, a rotating standard may be used instead. When the magnet to be tested is applied to the aluminum disk the speed of the moving element is proportional to the magnet strength. This gives a very simple and reliable comparative test for permanent magnets of this type. Many modifications of this method are possible, and will readily suggest themselves.*

1. The Determination of the Magnetic Induction in Straight Bars, Charles W. Burrows, *Bur. of Standards Bul.*, vol. 6, p. 31, October, 1909.

2. S. L. Gokhale, *Jour. A.I.E.E.*, p. 1170, December, 1924.

3. An Experimental Study of the Fahy Permeameter, Charles W. Burrows and R. L. Sanford, *Bur. of Standards Sci. Paper*, 306, p. 286, Aug. 27, 1917.

4. New Method of Testing Sheet Iron according to the Verband Regulations, van Lonkhuyzen, *Elektrotechn. Z.*, 32, pp. 1131–1134, Nov. 9, 1911.

5. Ewing, 3d ed., p. 366.

6. Practical Simplification of the Ballistic Method for Magnetic Measurements, A. Barbagelata, *Associazione Elettrot. Italian*, vol. X VII, June 30, 1913.

7. Apparatus for the Determination of the Magnetic Properties of Short Bars, M. F. Fischer, *Bur. of Standards Sci. Paper*, 458, (*Bul.* vol. 18, p. 513.) Nov. 15, 1922.

8. Ewing, 3d. ed., pp. 138–158.

9. Magnetic Testing of Straight Rods in Intense Fields, *Bur. of Standards Paper* 361, Feb. 21, 1920.

10. *Jour. I.E.E.*, vol. 54, p. 35, 1915.

11. A method of Producing Strong Magnetic Fields, P. L. Kapitza, *Proc. Royal Soc.*, p. 69, June 2, 1924.

12. "Dictionary of Applied Physics," vol. II, p. 463.

13. *Electrician*, vol. 17, London, 1916.

* For further details concerning specific apparatus for testing permanent magnets, Glazebrook's "Dictionary of Applied Physics" should be consulted.

CHAPTER XVIII

D.-C. TESTING DETAILS

The expert is distinguished from the ordinary workman largely by his attention to details and his knowledge of the best ways in which to perform the various operations of his trade. An attempt will be made in this chapter to give a description of some of those details which are essential for the magnetician to know if he is to do high-grade work. The results of many an otherwise fine piece of magnetic research have been rendered doubtful by the use of inaccurate and unsuitable testing apparatus and methods. In an extensive magnetic research, it is often possible to save many months of more or less routine testing by the proper choice of testing apparatus. For some purposes, the use of complicated and expensive apparatus is fully justified; in others, the use of the same equipment would be absurd.

Characteristics of Ballistic Galvanometers, Fluxmeters, and Volt-second Meters.—In the earlier magnetic testing, when galvanometers were used, they were generally of the moving-coil or D'Arsonval type. Any D'Arsonval galvanometer may be used as a ballistic instrument, but for the best results the galvanometer should have a long natural period and small restoring torque. If a charged condenser is connected directly to the terminals of a moving-coil galvanometer, the instrument will suddenly deflect and will then oscillate with decreasing amplitude, the amount of decrease depending largely on the air damping. If the galvanometer has a shunt connected to its terminals, the oscillations will decrease more rapidly, due to electromagnetic damping, or the dissipation of energy in the shunt resistance. If this resistance has such a value that, after its maximum deflection, the galvanometer just settles down to zero without oscillating, the galvanometer is said to be critically damped. If the shunt resistance is decreased to a much smaller value, the galvanometer is greatly overdamped, and, if sufficiently overdamped, it becomes what is known as a fluxmeter. Under this condition the galvanometer reaches its maximum deflection in a much shorter time, but returns to zero at a very much slower rate (see Fig. 184).[1]

Magnetic measurements may be made with the galvanometer underdamped, critically damped, or greatly overdamped; the last condition being much more desirable, in general. If an underdamped or critically damped ballistic galvanometer is used it is necessary, for the highest accuracy, that the current produced by the voltage induced in the search coil should all pass through the galvanometer before it has deflected by an appreciable amount. This is a condition difficult to attain for solid specimens of low-resistance material, unless the galvanometer has a very long period. If the galvanometer does have a very long period, it is very slow in its action, thus consuming much unnecessary time. For low-resistance specimens of solid material, many seconds may be required for the flux to build up to its maximum value, this lag being due largely to eddy-currents in the iron. If even a small specimen of pure iron is placed in a liquid-air bath, it may require 30 seconds or more for the flux to reach its maximum value because of the low resistance and consequent high eddies. Due to this difficulty, a greatly overdamped galvanometer or fluxmeter is now generally used for magnetic testing. The advantages are as follows, assuming that the restoring torque is very small with reference to the damping effect:

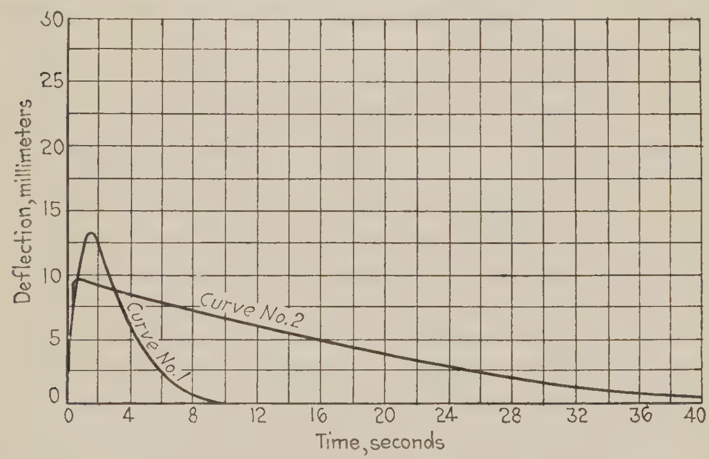

FIG. 184.—Relation between ballistic throw and time for a ballistic galvanometer. Curve No. 1, critically damped, Curve No. 2, over damped.

1. The deflections are practically independent of the time of discharge of the condenser or inductance.

2. The time required to reach its maximum deflection is much less.

3. The fluxmeter stays near its maximum deflection much longer, thus making it easier to read.

4. The deflections are nearly independent of the resistance of the circuit (within reasonable limits), thus making it possible to change from one sample to another without checking the resistance of the secondary winding or the fluxmeter calibration.

The galvanometer used as a fluxmeter is not quite so sensitive, but this is not a serious drawback since the sensitivity is usually much more than ample.*

For testing very large masses of material, such as the cores of large transformers, the rate of change of flux is very slow unless high voltages are used. Under these conditions even the slowest ballistic galvanometer or even a fluxmeter may not give satisfactory results. For this application, a volt-second meter may be used. This consists simply of a very light d.-c. armature, with a commutator, in a permanent-magnet field. It is really an integrating ammeter or milliammeter, but with sufficient resistance in series, so that it acts like a voltmeter. If such an instrument is connected to the secondary of a transformer, and slowly increasing d.c. is applied to the primary, a series of simultaneous observations of current and volt-second-meter readings may be taken. If, then, current is converted to units of m.m.f. and volt-second-meter readings to induction, a magnetization curve may be plotted. In a similar way a hysteresis loop may be obtained. The volt-second meter is calibrated by applying to it a known d.-c. voltage and noting the time required for a definite number of revolutions. If 1 volt for 1 second gives one revolution, then 1 revolution of the instrument, when connected to the secondary of a transformer, corresponds to a change of flux of 10^8 linkages (change of flux lines $\Delta\phi$, maxwells, $\times$ secondary turns N_2). This is independent of the time required to make the revolution; namely, the flux change is integrated. A practical application of the method has been described in the *A.I.E.E. Journal.*[2]

Methods of Calibrating Galvanometers and Fluxmeters.—The most common method of calibrating ballistic galvanometers and fluxmeters is by the use of a fixed or variable mutual inductance.

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* For a very complete discussion of the characteristics of galvanometers and fluxmeters, see the Leeds & Northrup Co. *Catalog* 2, pp. 3–36; and LAWS' "Electrical Measurements," p. 99.

The use of this method, together with formulas for calculating the desired primary currents or settings, has been given in Chap. XVII. If the mutual inductance consists of a long solenoid for the primary and a short coil wound either inside or outside of the solenoid at the center for the secondary, the mutual inductance may be calculated from the number of turns and dimensions of the coils. Unless, however, great care is exercised in the measurement of the dimensions, the required accuracy will not be obtained. It is more common, now, to buy calibrated mutual inductances wound on marble, or similar material, in the form of short cylinders. If the primary and secondary turns are put on side by side, the mutual and self-inductances of the coils all will be practically the same. If it is desired to have a mutual inductance which is not affected by stray fields, the coils may be wound on rings of insulating material. The mutual inductance may be either calculated or obtained by calibration. If variable mutual inductometers are desired with a long range and high sensitivity, the concentric brass cylinder arrangement described by Burrows[3] is very satisfactory. If less accuracy is permissible, the Brooks inductometer[4] is very useful.

When using the ballistic galvanometer, it is usually most convenient to arrange for critical damping. The galvanometer is shunted by the amount of resistance, as given usually by the manufacturer, for critical damping. The desired sensitivity adjustment is then obtained by putting a variable resistance in series with the parallel circuit. In the case of the fluxmeter, the circuits are often the same, but in this case the shunt resistance is very much less than the value for critical damping. The sensitivity may be adjusted by changing either the shunt or series resistance, or both.

A modification of the mutual-inductance method is that of Duddell. In this apparatus two sets of stationary coils are supplied with d.c. from a battery, the current being adjusted to a definite value according to the reading of an ammeter in series. Inductively coupled with the stationary coils are two moving coils which may be rotated rapidly 180 degrees by means of a spring. Electrically, the effect is the same as reversing the primary current, but the use of switches is avoided. The two systems of coils are arranged astatically.

Another similar method is embodied in the Hibbert Magnetic Standard. This consists of a permanent-magnet system having an annular opening through which the flux passes. An exploring coil connected to the galvanometer circuit is quickly drawn through this air-gap, and the resulting induced voltage produces a definite galvanometer deflection. This is simpler than the preceding arrangement in not requiring any field current. The permanency of the field magnet should be checked occasionally, however, since it might change due to aging or to the presence of stray fields.

In former years a so-called earth coil was used to some extent for the purpose of calibrating galvanometers. This consisted of a coil of wire which could be rotated rapidly 180 degrees in the earth's field. Its axis could be arranged so that either the horizontal or the vertical component of the earth's field was used. The disadvantages of this method are obvious; namely, the earth's field is readily disturbed by magnetic material in the vicinity, thus making its value uncertain; and the earths' field itself is slowly changing, thus requiring new determinations of its strength from time to time.

In order that the galvanometer sensitivity shall not be altered by changes in the resistance of the secondary circuit, it is customary to leave the secondary winding of the inductance or calibrating apparatus in circuit all the time. If this is done, the resistance of the secondary circuit does not need to be known.

If a ballistic galvanometer is calibrated by means of a mutual inductance consisting of a long solenoid primary and a short secondary winding, as described above, and is then connected to the secondary winding of the sample to be tested, Ewing gives the following formula for evaluating the gavalnometer deflections:

$$\Delta\phi = \frac{4\pi C n_3 A_3 N_4 R_2 d_2}{N_2 R_4 d_4}, \tag{83}$$

where $\Delta\phi$ is the change of flux in the sample in maxwells;

C is the current in amperes in the mutual-inductance primary which is either made or broken;

n_3 is the number of turns per centimeter of the primary of the mutual inductance;

A_3 is the mean area of the primary coil in cm.^{2};

N_4 is the total number of turns in the mutual-inductance secondary;

R_2 is the resistance in the secondary circuit when the test coil is connected to the galvanometer;

d_2 is the galvanometer deflection when connected to the test coil;

N_2 is the number of turns in the test coil;

R_4 is the circuit resistance when the galvanometer is connected to the mutual inductance;

d_4 is the galvanometer deflection caused by making or breaking C when the galvanometer is connected to the mutual-inductance secondary.

The simplification involved by leaving the mutual inductance in circuit all the time, thus eliminating the necessity of knowing R_2 and R_4, should be noted. Also, the simplification may be noted which results from expressing the mutual-inductance value in millihenries and calibrating the galvanometer so that, for instance, 1 kilogauss corresponds to a 1-centimeter deflection. A comparison of formula (75)* with formula (83) will show this. The above formula (83) will not hold for a fluxmeter, since the throw is not directly proportional to the resistance of the circuit. If the two R values are equal, however, it is correct.

If desired, the ballistic galvanometer may be calibrated by means of a condenser discharge. The galvanometer throw is proportional to the quantity of electricity discharged through the circuit, and this may be calculated from the condenser capacity and applied voltage. Due to condenser leakage and absorption effects, however, this is not, in general, as reliable and convenient a method as the mutual-inductance or similar methods, and is now used only in exceptional cases.

Galvanometer Illumination--Optical Systems.—Formerly, most testing with ballistic galvanometers was done by means of a microscope and scale. This now has been largely done away with, in favor of the lamp and scale, since the latter method is more convenient and less hard on the eyes. For short-scale distances or darkened rooms, the bright spot with the dark vertical line on a ground-glass scale, as supplied by a number of instrument manufacturers, is very satisfactory. This has the advantage that the scale is well illuminated. A concentrated-filament lamp may be used to advantage. Under less favorable conditions and for long-scale distances, the bright image of a straight filament is more satisfactory. The scale may be separately illuminated if desired. When two or three reflections are to be used, this is the only feasible method. In order to economize space, a right-angled prism or mirror may be placed in front of the galvanometer, the light reflected from the galvanometer mirror to a mirror on the ceiling, and then returned to a scale on the test table.

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* See p. 247.

A long-scale distance, especially with a fluxmeter, sometimes is of considerable advantage. When working to the highest available sensitivity, as with small ring samples, a long distance allows a longer scale to be used for a given angular deflection, and therefore produces less eyestrain for the same accuracy of reading. Again, since a fluxmeter should have as small a restoring torque as possible, the small angular deflections required assist in keeping this torque small. For samples of large viscosity, this is a very decided advantage. For long-scale distances and straight filaments, considerable difficulty is sometimes experienced due to the lens effect of imperfections in the bulb glass, even though tipless bulbs are used. Too much care cannot be exercised in the manufacture of these bulbs.

For the illuminated scales and dark lines, concave galvanometer mirrors or convex lenses in front of the mirrors must be used. There is also a double convex lens in front of the lamp with the dark line adjacent to a part of the lens mounting. For the filament-image method, a plane or concave mirror may be used, since the lens in front of the lamp will take care of the focus. In the case of the dark line, the focal distance is determined by the galvanometer mirror or combination of mirror and lens; in the case of the filament image, it may be anything desired, as determined by moving the lamp lens. For the latter case, a much better image will be obtained if the lamp is close to the galvanometer, at least for long-scale distances. When a concave galvanometer mirror is used and the scale distance is properly adjusted, no lens is necessary in front of the lamp.

Galvanometer Zero Adjustments.—For critically-damped ballistic galvanometers, the rate of return of the coil to zero is usually sufficiently rapid, except in special cases, so that it may be allowed to take its normal course. In the case of the fluxmeter, the return is so slow that either the galvanometer circuit must be opened and then closed as the coil passes its zero position, or the galvanometer may be kicked back by a second reversal of the magnetizing circuit. This latter method is the more common. Due to thermoelectric effects, leakage, etc., galvanometer zeros are always changing more or less. Also, reverse kicks do not bring the galvanometer back to its original position, due to drift while deflected. It is common, therefore, to have a small adjustment of the scale by means of a rack and pinion or similar device. In the case of the fluxmeter, the exact true zero does not need to be reached for ordinary accuracy of testing, and the zero is usually set by moving the scale or by some other external means before each deflection. If desired, the galvanometer may be brought back to zero by means of a coil and permanent magnet or some similar means. Gokhale has used a copper disk provided with slip rings which is rotated in a magnetic field. The resulting e.m.f. brings the galvanometer to the desired position. For large changes in zero, high-grade galvanometers are provided with tangent screws connected to the top suspension support.

Elimination of Vibration.—In order to avoid trouble, when possible galvanometers should be located in positions where vibrations are not of sufficient magnitude to be appreciable. In most cases a shelf fastened to a wall is quite satisfactory. In others a brick or concrete pier, either set on the floor or on its own foundation, is satisfactory. Often, however, special means have to be taken to eliminate the effects of vibration. If necessary, the well-known Julius suspension may be used. This is a specially designed platform supported from the ceiling or a wall bracket by fine steel wires. The galvanometer coil is located at the center of gravity of the platform. Swinging due to air currents is reduced by damping vanes in oil.

If only a temporary device is required, even very severe vibration may be eliminated by means of a heavy shelf made of concrete or other similar material, which is supported from the ceiling by three or preferably four ropes. Turn buckles should be provided for equalizing the strain on the ropes, since they may stretch unequally. Swinging may be readily prevented by vertical plates fastened to the under side of the shelf which dip into cans or jars filled with cotton or waste.

In some cases vibration may be sufficiently reduced by setting the galvanometer on a plate supported by tennis balls. Often, rather severe vibration may be almost completely eliminated by placing the galvanometer on a shelf supported by ordinary rubber sponges. Due to its simplicity and effectiveness, this is perhaps the first remedy which should be tried. The chief disadvantage of the sponges is that they are gradually compressed, thus changing the galvanometer level.

Demagnetizing Practice and Criteria.—If tests are to be made at inductions lower than those to which the sample previously has been subjected, the sample first must be demagnetized unless tests are to be made only well above the point of maximum permeability. Referring to Fig. 185, the necessity for demagnetizing samples is evident from the properties of displaced hysteresis loops. Suppose the specimen has been magnetized to B_m, and the m.m.f. is then removed. The flux will drop to B_r (assuming no gaps in the magnetic circuit). Now, if there is applied an m.m.f. equal to H_1, the flux will go to *b*. If H_1 is then reversed to H_1', the flux will go to *c*. If H_1' is again reversed, the flux will go to *d*. The apparent induction then will be one-half the vertical distance between *d* and *c*. Now, if the sample had been in the normal state, the reversal of H_1 and H_1' would have produced the loop *e-f*, having a considerably larger vertical distance between *e* and *f* than was the case for *c* and *d*, in accordance with the known properties of displaced hysteresis loops. Points *e* and *f* are obviously on the normal induction curve.

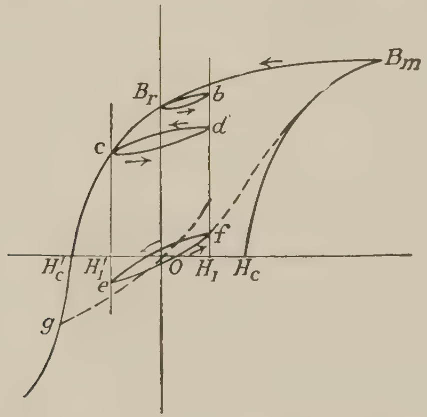

FIG. 185.—Illustrating the necessity for demagnetization.

In order to bring the sample down to the normal state, it is necessary to continually reverse the magnetizing force, at the same time gradually reducing it. For permanent-magnet steels and material with very high initial permeability, this should be a very gradual process. The care needed is dependent, of course, on the accuracy required. It might be supposed that it would be sufficient to reduce the flux to a point *g*, and then increase it to *O*. It has been shown conclusively, however, by several investigators, that the steel under this condition is not in the normal state; namely, the line *g-O* does not coincide with the normal induction curve *O-f*, but is steeper.

When large numbers of samples are to be tested, an automatic reversing switch operating at a definite speed, such as 1 reversal per second, may be used.[5] For solid materials, where the eddy-currents are of considerable magnitude, the rate of reversal should be quite slow. The minimum time between reversals can be determined approximately by reversing the magnetizing current and then closing a switch connecting the galvanometer to an exploring coil on the sample. When the interval is long enough, so that only a small deflection results, the time is sufficient.

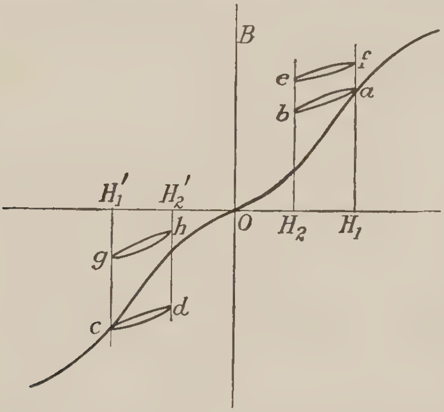

FIG. 186.—Illustrating the method of determining the degree of demagnetization.

If a sample has been demagnetized and it is suspected that sufficient care was not taken, the operation may be repeated using a slower rate of decrease of the demagnetizing current. If the apparent permeability for a given magnetizing force is then higher, the original demagnetizing was done too hastily. Another test for complete demagnetization is one described by McKeehan.[6] If the specimen is in the normal state (see Fig. 186) and a d.-c. magnetizing force H_1 is applied and then is reduced to H_2, there will be a change of induction from *a* to *b*. If there is then applied a negative value H_1' equal to H_1 and this is reduced to H_2', where $H_1 - H_2 = H_1' - H_2'$, there is obviously a change of induction from *c* to *d*. Under normal conditions ΔB is the same for both cases. If, however, there is still some residual induction present in the specimen, due to the previous magnetic history, a pair of loops, such as *e-f* and *g-h* may be obtained. According to the known laws for displaced hysteresis loops, ΔB for *e-f* will be less than for *g-h*, indicating incomplete demagnetization.*

As shown by Burrows,[5] when a demagnetized specimen has applied to it a d.-c. magnetizing force, called by Burrows the polarizing force, greater than the particular value which is to be used for determining *B*, there results a decrease in induction, when the particular *H* value is reversed, over that which would occur with the specimen in the demagnetized state. It is obvious that the decrease in induction is due to displacement of the hysteresis loop due to residual induction, as explained above. This effect is shown by Fig. 187. Obviously for large polarizing forces the decrease becomes constant due to the fact that the retentivity approaches saturation, as discussed in Chap. III. Now, suppose that the correct procedure for demagnetizing is gone through for

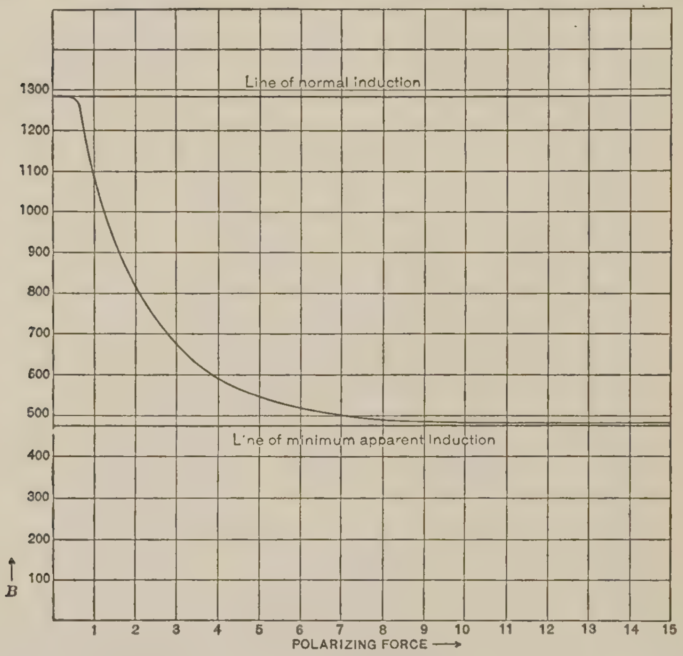

FIG. 187.—Showing the relation between the polarizing force and the apparent induction in annealed transformer iron for $H = 0.5$.

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* Burrows has given a very complete discussion of the subject of demagnetization. His paper should be consulted by anyone interested in going into the details of the art.

various values of maximum demagnetizing force, after a large polarizing force has been applied (see Fig. 188). Down to a certain critical value of maximum demagnetizing force, constant maximum induction for the given H value (0.5) results. For lower maximum values, however, down to 0.5, there is a decrease in induction when H = 0.5 is reversed, as shown by the curve of upper limits. The point at which the break occurs in the upper horizontal line is termed the critical demagnetizing force. This

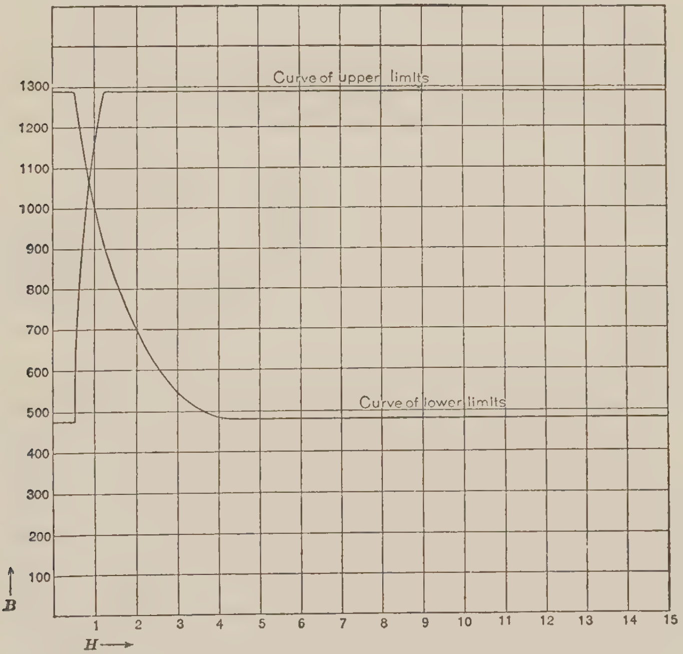

FIG. 188.—Showing the influence of the upper and lower limits of the demagnetizing force on the apparent induction of annealed transformer iron. $H = 0.5$.

critical demagnetizing force corresponds to an induction somewhat over the value at which maximum permeability occurs. It is evidently a function of the retentivity and is probably not far from the maximum value of B_r.

If, now, the demagnetizing force is carried down to various minimum values before testing with the $H = 0.5$ value, the curve of inductions marked "curve of lower limits" will be obtained (Fig. 188). Evidently, the lowest demagnetizing force necessary is 0.5 or the value which is to be used for testing, and there is no object in carrying it lower. Figure 188 is typical, but the curves vary enormously in actual magnitude depending on the hardness of the material.

Complete demagnetization cannot be obtained, in general, with 60 cycles, or even 25 cycles. A satisfactory speed of reversal for general work is 1 cycle per second. It may be greater for thin, high-resistance samples, and should be less for large samples of low resistance. If commercial frequencies are used, often, due to skin effect, the flux cannot penetrate to the center of the specimen, and therefore complete demagnetization is impossible.

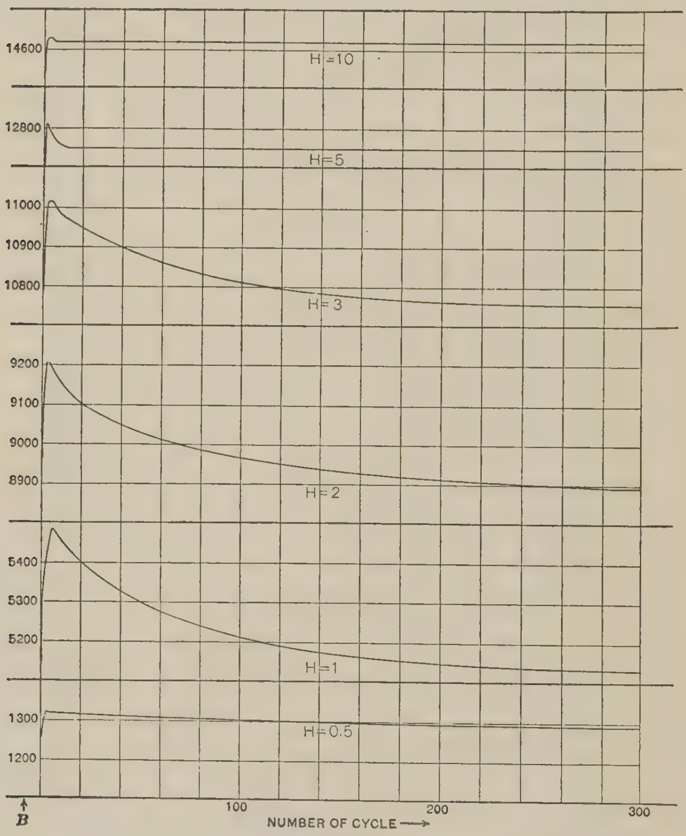

FIG. 189.—Showing the manner in which demagnetized transformer iron approaches the cyclic state for various values of *H*.

When a sample is completely demagnetized, the first few succeeding slow reversals for a definite value of *H* produce an increased induction (see Fig. 189). Very soon, as the reversals are continued, the induction decreases; and after the reversals come to a steady state, the final value is termed by Burrows the true value of the normal induction. The initial value is evidently very nearly the same as the final value in many cases.

Vibration is not very effective as a demagnetizing agent, although for many materials it will cause a considerable decrease in residual induction. The re-application of a definite polarizing force entirely wipes out the effect of previous vibrations.

Burrows gives the following instructions for the demagnetizing procedure:

> The demagnetization should be accomplished by a current reversed at the rate of approximately 1 cycle per second, while gradually diminished in such a way that the rate of decrease of the induction is as nearly as may be uniform. An ammeter in circuit and a rough estimate of the shape of the *B-H* curve will enable one to regulate the rate of decrease of current with sufficient exactness. The initial demagnetizing current should be sufficient to carry the induction beyond the knee of the *B-H* curve, and the final current should not be greater than the smallest magnetizing current to be used.
>
> The full demagnetization may be accomplished in about 90 seconds.
>
> Now, apply the lowest magnetizing force desired and reverse at the same speed as in demagnetizing. At intervals get a ballistic deflection. Continue this until 2 deflections about 25 reversals apart show only a negligible difference. This final deflection is the normal induction.
>
> Without demagnetizing again, apply the next larger magnetizing force and reverse as before. Continue in this way till all the required points on the curve have been obtained.

Air Correction and Automatic Compensation.—In the ballistic method of test, the inductions are measured by means of an exploring coil which surrounds the sample. In general, the mean cross-section of the coil is considerably larger than the cross-section of the sample. At high inductions, a very appreciable amount of flux passes through this coil outside of the sample. It is equal to the m.m.f. times the difference in cross-section of the coil and the sample. In order to obtain the true flux in the sample, this leakage flux must be subtracted from the total induced flux. This is easily done by means of the following formula:

$$B_{\text{true}} = B_{\text{obs}} - KH, \tag{84}$$

where B_{true} = the true induction in the sample in gausses;
B_{obs} = the apparent induction;
H = the m.m.f. in gilberts per centimeter;

$$K = \frac{a - A}{A};$$

a = the mean cross-section of the test coil in square centimeters;

A = the cross-section of the sample in square centimeters.

For small samples or laminated material, the cross-section a is best determined from the weight and density of the sample. A may be calculated from the dimensions of the coil or, better, measured by placing the coil in a known magnetic field produced by a solenoid or other convenient means and then determining the linkages ballistically, from which the area may be calculated.

For hysteresis loops, the method is similar. Assume that the ΔB values are always determined from the tip B_m of the loop. B_m is determined as a point on the normal induction curve and is the true B_m; namely, corrected for air leakage. Then, any point on the loop equals

$$B_{\text{true}} = B_m - [\Delta B_{\text{obs}} - K(H_m \pm H)], \tag{85}$$

where ΔB_{obs} is the apparent change in induction.
It should be noted that for negative values of H, H_m and H are added numerically.

The formula may be written, if desired,

$$B_{\text{true}} = B_m - [\Delta B_{\text{obs}} - K\Delta H]. \tag{86}$$

If preferred, the compensation for air leakage may be made automatically in the case of ring tests and for certain types of permeameters, as for instance, the Burrows. For illustration, consider the application of an automatic compensator to the Burrows permeameter. It will be remembered that for this permeameter H is proportional to the main magnetizing current, since the reluctance of the yokes and joints is completely compensated for by means of other windings. Suppose that the main magnetizing current passes through the primary of a variable mutual inductance the secondary of which is in series opposing the B exploring coil. Assume that this mutual inductance is so adjusted that when the primary current is reversed, an e.m.f. will be generated in the secondary just equal to that generated in the B coil due to the air-leakage flux, namely the linkages of the mutual inductance (millihenries × 10^5) are equal to the air-leakage flux between the sample and B coil. Under this condition the values indicated by the ballistic galvanometer will be the true induction values, since the correction for air leakage is proportional to H.

In the case of the Burrows permeameter as used by the Westinghouse Electric and Mfg. Co., both for research work and commercial testing of laminated material, an automatic compensator is used which is a variable mutual inductance wound on a bakelite ring and having various taps so adjusted that when the dial to which the taps are connected is set to correspond to the weight of sample (to the nearest 25 grams) the air-flux compensation is automatically made. This makes it possible to obtain H values corresponding to different B values without any calculations and without plotting curves and interpolating. This is of especial value in commercial testing. If desired, the automatic compensator may be set so that $B_f(B\text{-}H)$ instead of B will be read. The method is to increase the mutual-inductance value to correspond to the total area of the search coil instead of the difference of the total area and the sample area. This same method is used in Gokhale's saturation permeameter.

Variable Mutual Inductometers.—When a variable mutual inductometer having a long range and an accuracy of setting of 0.1 per cent or better is required, the type devised by Burrows in connection with his permeameter is quite satisfactory. This consists of two concentric brass cylinders about 6 inches in diameter and so arranged that the inside one, which carries the secondary winding may be moved up and down by means of a centrally located screw. This screw carries a pointer for reading fractions of a revolution and the inside cylinder another pointer which passes over a vertical scale, thus giving the revolutions. Taps are brought out from the primary winding on the outside cylinder in order to give various ranges. As ordinarily constructed, a range of from 0.1 to 75 millihenries is obtained.* This instrument, of course, has to be used with calibration curves. One of these inductometers which has been in constant use for 8 years has not changed its calibration by more than 0.05 per cent of full scale reading in that length of time.

When less accuracy of setting is required, the Brooks inductometer, as manufactured by several instrument makers, is very satisfactory. This has a scale about 8 inches in diameter which covers about 300 degrees. Except at the extreme ends, the scale is practically uniform. These inductometers may be obtained to cover any desired range within reasonable limits. The construction is such that only slight changes in calibration are produced by wear of the bearings. The arrangement of the coils is such that external magnetic fields have a very small effect.

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* For a complete description of this inductometer, see *Bur. of Standards Sci. Paper* 117.

For inductometers which may be varied in steps, a satisfactory construction is to wind the primary and secondary coils on toroidal forms made of marble or for less accurate work moulded bakelite material. Taps may be brought out as desired. The advantage of this construction is that the instrument is not affected by stray fields unless they are very concentrated and nonuniform.

The well-known Ayerton and Perry variable inductometer has been widely used for a.-c. bridge work, but is not particularly suited to magnetic measurements. As ordinarily constructed, it has a nonuniform scale and is easily affected by stray fields.

Many other forms of inductometers have been devised, but the above-mentioned ones will be satisfactory, except for special cases such as high-current applications, when some special construction would be required.

Switching Devices.—The principal requirement of a permeameter switch, both for primary and secondary circuits, is nonvariability of contact resistance. Mercury switches have been much in favor for this purpose in the past. The original Burrows permeameter used special rocker mercury switches which were fairly satisfactory, provided they were cleaned occasionally. One of the objections to a mercury switch in a primary circuit is the possibility of mercury poisoning due to mercury vapor produced by arcing at the contacts. Mercury switches operating in a vacuum (glass container) or in some sort of nonoxidizing gaseous atmosphere have recently been devised. These are very satisfactory for certain purposes, especially if the break is from mercury to mercury. One serious limitation is that they will handle only small d.c., especially when used in inductive circuits.

If properly constructed, rocker-knife switches with copper blades are fairly satisfactory; however, they do have to be cleaned occasionally. They may be lubricated with vaseline to advantage, if the contacts begin to wear rapidly. For ring tests currents of several hundred amperes may be readily handled by such switches. For high-inductance permeameter magnets, however, only a few amperes are permissible.

Kowenhoven[7] recommends a snap switch immersed in oil for controlling permeameter primary currents. Such construction seems to offer some possibilities. Snap and quick-break switches, however, are apt to be rather weak mechanically.

Mercury switches for the secondary circuits are seldom found now, outside of some of the university laboratories. Baby-knife switches are fairly reliable for this purpose and give little trouble. The tendency seems to be toward the use of switches such as have been developed for telephone work and radio, as, for instance, ringer keys and anticapacity switches. Such switches are very compact and give very little trouble due to poor contacts. They may be highly recommended for the secondary circuits of permeameters.

Effect of Solid Masses in Permeameter Circuits.—When a ballistic galvanometer is used for magnetic testing, it is essential, as has already been shown, that the rate of flux change should be rapid. If the yoke and poles of a permeameter are made of solid material or unslotted brass, or other conducting material is used to support the coils, induced eddy-currents will be produced in the metallic members which may very greatly slow up the rate of flux change. This has been very clearly shown experimentally by Kowenhoven and Berry.[7] A lag of flux of as much as 1 second was found in some cases, due to solid masses in the permeameter magnetic circuit. If a fluxmeter is used, this is probably of little or no importance except perhaps when using a null method.

Very excellent permeameter performance may be obtained by the use of laminated high-resistance steel (4 per cent silicon for instance) for the yokes and poles, and micarta tubes and plates for the coil supports. The laminations may be riveted together and the surfaces ground without producing appreciable harmful effects due to short-circuiting the laminations.

Effect of Strains.—For solid test bars, unless the pole pieces are self-aligning, it may happen that tight clamping will introduce bending strains of considerable magnitude into the specimen. As shown in a previous chapter, bending strains much below the elastic limit, will often very greatly alter the magnetic properties. Care must be exercised that this condition shall not occur, especially for high-permeability material. For permeameters in which the joint reluctance is compensated, it is better, in general, to clamp the samples very loosely, in order to avoid bending strains.

In the case of laminated material, bending strains are very likely to be of considerable magnitude, due to the fact that the strips of material are never perfectly flat and the ordinary methods of clamping almost invariably introduce bending strains. When the permeameter construction permits, it is usually better to clamp the specimens lightly on the edges rather than on the sides. This allows good magnetic contact without introducing bending strains. In this case, the individual strips need not be pressed together, but may be separated as far as necessary in order to leave room for the natural waviness of the material.

In the case of ring samples of laminated material, it is often advisable to make a cardboard form surrounding the laminations on which to wind the coils. Otherwise, the pressure applied by the turns may produce considerable bending strains if the rings are not perfectly flat. Without this precaution, cases have been known where the maximum permeability has been reduced as much as 50 per cent.

Errors in Ring Samples.—Due to the fact that in a ring sample the length of the magnetic path is less toward the inside, the m.m.f. per unit length will be greater for the smaller circumferences, and the flux density will be higher toward the inner portion of the ring. If it is assumed that the length of magnetic path is equal to the mean circumference of the ring and that the flux density is equal to the total flux divided by the total cross-section of the sample, certain errors will be introduced into the magnetic measurements, both with reference to permeability and to hysteresis loss. M. G. Lloyd[8] has calculated these errors on the basis of constant permeability, and has shown what ratio of radial width to diameter of rings is necessary to reduce these errors to a negligible amount, as shown by the following tables:

TABLE XXIII.—RATIO OF THE AVERAGE VALUE OF H TO THE VALUE AT THE MEAN RADIUS IN RINGS OF RECTANGULAR AND CIRCULAR SECTION

P*	$\frac{H_0}{H_R}$	
	Rectangular	Circular
½	1.0986	1.0718
⅓	1.0397	1.0294
¼	1.0216	1.01625
⅕	1.0137	1.0102
⅙	1.0094	1.0070
⅐	1.0069	1.00515
⅛	1.0052	1.0040
⅒	1.0033	1.0025
1/19	1.0009	1.0007

* P is the ratio of radial width to mean diameter of ring. In order to keep the errors within 1 per cent, P should be not greater than one-sixth. Due to variations of permeability with induction, the nonuniformity of flux distributions will be greater for low inductions and less for high than on the assumption of constant permeability.

TABLE XXIV.—RATIO OF HYSTERESIS LOSS WITH UNIFORM DISTRIBUTION OF FLUX TO THE ACTUAL LOSS, ASSUMING CONSTANT PERMEABILITY, IN RINGS OF RECTANGULAR AND CIRCULAR SECTION

P	$\frac{W_0}{W}$	
	Rectangular $\eta^* = 1.6$	Circular $\eta = 1.5$
½	1.1117	1.0841
⅓	1.0447	1.0327
¼	1.0244	1.0183
⅕	1.0153	1.0114
⅙	1.0105	1.0077
⅐	1.0076	1.0058
⅛	1.0059	1.0041
⅒	1.0035	1.0023
1/19	1.0012	1.0008

* η is the Steinmetz exponent. The results are very nearly the same whether it is taken as 1.5 or 1.6. Here, again, it is seen that, for a 1 per cent error, P should not be over one-sixth.

1. Leeds & Northrup Co. *Catalog* 20, p. 15.

2. The Effect of Displaced Magnetic Pulsations on the Hysteresis Loss of Sheet Steel, L. W. CHUBB and THOMAS SPOONER, *Trans. A.I.E.E.*, vol. XXXIV, Part II, p. 2671, 1915.

3. The Determination of Induction in Straight Bars, C. W. Burrows, *Bur. of Standards Bul.*, vol. 6, p. 31, 1909.

4. A Variable Self and Mutual Inductor, H. B. Brooks and F. C. Weaver, *Bur. of Standards Sci. Paper*, 290, March, 1917.

5. On the Best Method of Demagnetizing Iron in Magnetic Testing, Charles W. Burrows, *Bur. of Standards Sci. Paper* 78, January, 1908.

6. Demagnetization and Hysteresis Loops, L. W. McKeehan and P. P. Cioffi, *Jour. O.S.A. and R.S.I.*, p. 479, October, 1924.

7. Oscillographic Study of the Current and Voltage in a Permeameter Circuit, W. B. Kowenhoven and T. L. Berry Jr., *Jour. A.I.E.E.*, p. 1304, December, 1923.

8. Errors in Magnetic Testing with Ring Specimens, Morton G. Lloyd, *Bur. of Standards Bul.*, 3, vol. 5, p. 435, 1908.

CHAPTER XIX

CRITICAL EXAMINATION OF TEST METHODS

Choice of Method of Test.—For intrinsic accuracy and simplicity, the ring test is unexcelled. There are, however, several reasons why this is not always the best method to use. The chief ones are as follows:

1. Unless it is feasible to use very small samples or low magnetizing forces, the labor of winding the samples is often so great as to preclude the use of this method except for certain types of research work where accuracy is the chief factor. If small samples are used, especially if they are of laminated material, they must be annealed before testing to remove punching or machining strains.
2. When it is desired to test laminated material without re-annealing after punching or shearing, ring samples are practically out of the question, except for special purposes, since the radial width of samples should be not less than 1 inch, and preferably more, which requires a mean diameter of 6 inches or greater, as shown in the previous chapter.
3. When tests are required with the flux parallel to or at some definite angle with reference to the direction of rolling or drawing of the sample material, ring specimens cannot be used. In this case a long solenoid using either the magnetometer or ballistic method, or some form of permeameter must be employed.
4. When it is desired, as is generally the case for commercial acceptance tests of sheet material, to use the same samples for permeability tests as for the Epstein core-loss tests (see Chap. XX), a permeameter should be used.
5. Permanent-magnet steel in its usual bar form lends itself much better to permeameter tests than to ring tests, due to the difficulty and expense of machining suitable rings and to the fact that it is desirable to heat-treat specimens with approximately the same cross-section as are to be used for the finished magnet.

In spite of these limitations, the ring test finds many useful applications. For research work on magnetic materials, especially if they have high permeability and low hysteresis loss, ring samples are very suitable, since much higher accuracy may be insured and, as previously pointed out, small samples are generally satisfactory for such work. Under these circumstances the total time required for preparing and testing samples is little or no greater than if a permeameter is used. One of the chief advantages of the small rings is that many samples may be prepared from a single small experimental heat of material. This is of especial advantage when various methods of heat-treatment are to be studied.

When it is desired to sample a forging or casting, often a small sample from which a ring can be readily made may be obtained by means of a hollow drill. A low-temperature anneal, to remove the machining strains, will not very materially alter the magnetic properties from their original values.

When considering the choice of a permeameter, several things have to be taken into account. For routine acceptance tests, absolute accuracy may be sacrificed, if necessary, for speed and reproducibility of results. Under certain shop conditions it may be undesirable to use a delicate instrument such as a ballistic galvanometer. For some kinds of routine testing a permeameter capable of measuring only permeability is entirely satisfactory, thus eliminating the complications which often result when hysteresis determinations are also required. For laminated material, the permeameter should be capable of taking samples at least as wide as Epstein strips (3 centimeters, or 1$\frac{3}{16}$ inches) due to the fact that these strips are generally available without preparing separate samples and because of the desirability of using wide samples in order to reduce punching strains.

For research work, in order to be able to compare results readily with those of other investigators, a permeameter should give results of high absolute accuracy as well as of high reproducibility. Some sacrifice of convenience, simplicity, and speed is permissible for such work. The necessity of using standard samples should be avoided if possible, except where many specimens of the same kind of material are to be compared. A permeameter giving the required accuracy without the use of correction or shearing curves is greatly to be desired, since the application of such curves requires time and the choice of curve depends on the magnetic quality of the material being tested, thus introducing an element of doubt as to the accuracy of the results.

For uniform material having a maximum permeability of less than 10,000, the Burrows double-yoke and the Fahy Simplex permeameters fill all of the above-mentioned requirements and are suitable both for routine acceptance tests and for research work. If built to take larger samples, probably the Niwa and perhaps the Iliovivi permeameters would be satisfactory. For comparison of specimens with a standard sample, the Fahy Duplex instrument is very convenient. For ease of operation, the Fahy Simplex is superior to the Burrows. For material of very high permeability, the Burrows apparatus shows considerable errors in the region of maximum permeability. For permeameters using the magnetic potentiometer principle, such as the Simplex and Niwa, the sensitivity is rather low for high-permeability material. Due to this sensitivity factor, the Burrows instrument is superior for tests at very low inductions. Due to the ease of applying air-leakage compensation and to the fact that it is possible to set the instrument for definite values of H, the Burrows permeameter is more suitable for some applications than are the others. It has the serious disadvantage for many applications that it requires two identical samples, or if two somewhat dissimilar samples are used, a much more laborious test procedure is necessary. The Burrows and Fahy permeameters evidently give results which have high absolute accuracy, and for uniform samples the test results are practically identical.

All types of direct-reading permeameters, so far developed, such as the Koepsel, Esterline, etc., require correction curves which are different for each class of material tested. What is gained in speed and ease of reading is lost, due to the necessity for these corrections and the resulting uncertainty in the results. For this reason, the ballistic type of permeameter has very largely superseded the direct-reading type for routine and research work, at least in America. If a large number of similar samples of low-permeability material are to be tested, of course, a direct-reading permeameter often may be used to advantage. In this case the corrections need not be made when only comparative results are required.

For permanent-magnet steels, a direct-reading permeameter may be entirely satisfactory, since such materials are very easy to test, due to their low permeability and the consequent reduced effect of joints in the permeameter's magnetic circuit. The magnetic potentiometer types of permeameter, however, are quite satisfactory for magnet steels and are probably nearly as quick to operate as the direct-reading types.

Accuracy Tests for Permeameters.—In order to obtain a check on the accuracy of a given permeameter, several methods may be used. One of the simplest is to use samples which have been standardized by means of an absolute permeameter, such as the Burrows. For long thin samples, a magnetometer method may be used for standardizing the samples. In order to obtain high accuracy for the magnetometer tests, if the samples are not very long with reference to the diameter, an ellipsoidal form must be used. In order to apply such a sample to an ordinary permeameter, it would have to be machined to a cylindrical form, and this machining operation would probably alter the magnetic properties. This is not, therefore, a good method of checking.

If the permeability is not too high, it is possible to use a hollow rod inside of which is placed a solenoid having a large number of turns of very fine wire. The H values may be measured by connecting a ballistic galvanometer to this coil. These, compared with the H values as measured by the permeameter in the ordinary way, give the error.

For tests of high-permeability material,[1] a method has been devised making use of link samples which is very satisfactory, provided sufficient care is taken to obtain uniform samples. Such a sample is shown by Fig. 170. This sample is supplied with a uniformly distributed primary and secondary winding and tested like a ring. It is then placed in the permeameter under investigation and tested like a bar. The limitations of a Burrows premeameter for high-permeability material have been determined in this way. Also, the errors in applying the Burrows principle have been investigated when using nonuniform samples. If a sample has a higher permeability in the center then toward the ends, due to the method of compensation employed by the Burrows permeameter, much higher permeabilities may be indicated than those which the sample actually has, even at the most permeable portion.

Summary.—For experimental work on new magnetic materials, or for samples of sheet or solid material having very high permeability, the ring sample, in general, is best. For commercial acceptance tests on sheet material, the Burrows or the Fahy Simplex permeameter is quite satisfactory. Some of the other permeameters working on the magnetic potentiometer principle, when they are built for samples at least 3 centimeters wide, also probably will be satisfactory. For solid material, the Fahy Simplex, due to its greater simplicity, is usually preferable to the Burrows. For the comparison of many samples very nearly alike, or for permanent-magnet steels, one of the direct-reading permeameters, such as the Koepsel, often will be quite suitable, though, other things being equal, it is better to use a permeameter which requires no correction to give absolute values. For high inductions and for very high coercive-force material, a permeameter of the Campbell and Dye type, such as developed by the Bureau of Standards, is quite satisfactory. For extremely high inductions, the Ewing isthmus method or an ellipsoid in a concentrated field may be used. For very low inductions and the measurement of initial permeabilities, a ring sample is usually most satisfactory. For very short bar samples, the Bureau of Standards method described in the previous chapter is useful. For the study of magnetic changes with temperature, the magnetometer method may be used to advantage, as has been done so successfully by Honda, though the ballistic method may also be used, if sufficient care is taken with the insulation of the windings. For further suggestions as to the most suitable methods of test at other than normal temperatures, a recent article by Terry should be consulted.[2]

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1. Methods of Magnetic Testing, Thomas Spooner, *Elec. Jour.*, vol. XVIII, p. 351, August, 1921.

2. Methods of Measuring the Effect of Temperature on Magnetic Properties, Earle M. Terry, *Jour. O.S.A. and R.S.I.*, vol. 11, 1, p. 67, July, 1925.

CHAPTER XX

A.-C. TEST METHODS

Ballistic methods and permeameters, while yielding much useful data concerning magnetic materials, do not give complete information. For the commercial inspection of laminated materials which are to be used largely under alternating-flux conditions, a.-c. tests are much more widely used than d.-c. tests, partly because the former are, in general, easier to apply and partly because they yield more information concerning the performance of the material in the completed apparatus. Hundreds of tons of electrical sheet steel are sold each year on the basis of an a.-c. magnetic inspection only.

If a sample of magnetic material is subjected to an alternating flux, the following losses will occur:

1. Hysteresis.
2. Eddy-current.
3. Apparent.

For most commercial purposes it is sufficient to test for total core loss under standard conditions without separating the hysteresis and eddy-current losses. When it becomes necessary, however, there are several methods available for making this separation which will be discussed in detail later. It is customary in America to test electrical sheet steel at a maximum induction of 10 kilogausses and a frequency of 60 cycles, the corresponding core loss being denoted by the symbol $W_{10/60}$. In Europe the material is usually tested at an induction of 10 and sometimes 15 kilogausses and a frequency of 50 cycles.

Apparent loss is not so well known or generally used a quantity as true loss, but it is useful in transformer design for calculating the exciting current. It is equal to the product of the volts and amperes in a magnetizing winding surrounding a definite weight of core material for a given induction and frequency. In the finished apparatus the apparent loss is a function not only of the intrinsic quality of the material, but of the number and size of air-gaps in the magnetic circuit. Apparent-loss factors, therefore, have to be applied with caution.

Hysteresis and eddy-current losses may be expressed by the following well-known formula:

$$W = K_1 f B^x + K_2 f^2 t^2 B^y, \tag{87}$$

where K_1 and K_2 are constants;

f is the frequency;
t is the thickness of laminations.

For moderate inductions $x = 1.6$ (Steinmetz exponent) and $y = 2$ approximately. For commercial sheet steel the 1.6 law for hysteresis will hold approximately for ranges of induction from 1 to 12 kilogausses. Outside of this range the law fails to express the facts with any degree of accuracy. K_1 is the Steinmetz coefficient η. K_2 is approximately inversely proportional to the resistivity of the material, but for thin sheets with large grains, the departure from this relation may be large.*

Effect of Form Factor.—If a specimen of laminated magnetic material is provided with a magnetizing winding which is connected to an a.-c. voltage supply, hysteresis and eddy losses will be produced in the core, which are a function not only of the frequency and magnitude of the voltage, but also of the shape of the voltage wave, as discussed in considerable detail by Lloyd[1] and others.

By theoretical and experimental analysis, it may be shown that the hysteresis loss in the material is a function of the r.m.s. voltage (assuming no resistance in the circuit) divided by the form factor of the voltage wave; where the form factor is equal to the r.m.s. voltage divided by two times the average voltage of the half wave (E_{av}). This is evident from the ordinary formula for induction and the fact that hysteresis loss is proportional to the maximum flux density.

$$B_m = \frac{10^8}{f \times N \times A} \times \frac{E_{rms}}{ff}. \tag{88}$$

Now, since the form factor ff is equal to the ratio $\frac{E_{rms}}{E_{av}}$, B_m is proportional to the average value of the half voltage wave. For a sine wave of voltage, the form factor equals 1.11 (1.107). If a voltage wave has a form factor of over 1.11, it is called peaked (since, in magnetic work, such a wave usually looks more pointed than a sine wave), and if the wave has a form factor of less than

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* For further details concerning normal hysteresis and eddy-current losses, refer to Chap. III.

1.11 it is called flat. A rectangular wave has a form factor of 1.00, which is the minimum possible form factor.

The hysteresis loss only is a function of the form factor, the eddy-current loss being proportional to the r.m.s. voltage regardless of the form factor. This offers a means of separating hysteresis and eddy losses which will be discussed in detail later.

It is customary to refer iron losses to the standard basis of a sine shape of supply voltage. From the above discussion it is evident that it is not essential that the voltage wave should be a sine, but only that it should have the same form factor as a sine wave; namely 1.11. As a matter of fact, quite a distorted wave is capable of giving the same iron loss as a sine wave.

If a voltage wave is peaked (using peaked in the above-mentioned sense) the corresponding flux wave, in general, will be flat. This means a lower maximum induction, and therefore a lower hysteresis loss. If, on the other hand, the voltage wave is flat, the flux wave will be peaked, which means an increased hysteresis loss. When a magnetic core is operated at high-flux densities, the harmonics in the exciting current acting on the resistance of the circuit tend to produce a peaked voltage wave at the terminals of the core winding. Under conditions of saturation, therefore, the core losses will tend to be less than would be expected from the r.m.s. voltage.

In order to determine the exact flux acting on the magnetic core, the voltage to be considered should be that produced in a secondary winding surrounding the core, since this is a direct function of the flux. If the applied voltage is used, the harmonics of the exciting current and the IR drop in the primary winding due to these harmonics must be considered.

It has been proposed to reduce transformer core losses by using a peaked voltage supply. Due to telephone interference and other reasons, however, harmonics in the voltage supply, in general, are undesirable. This method of reducing core losses, therefore, has found no favor commercially.

Iron-loss Voltmeter.—Since it is often difficult or impossible to obtain a sine wave of voltage supply for testing transformers, L. W. Chubb some years ago devised a very simple instrument, called an iron-loss voltmeter, which makes possible the determination of the core loss of a transformer which would occur under sine-wave conditions by a test with any convenient commercial circuit. The principle of this device is illustrated by Fig. 190.

The secondary of the transformer under test is connected to the terminals of the iron-loss voltmeter as indicated. These terminals are connected internally to two primary windings on a laminated iron core having a closed magnetic circuit. By means of a switch, not shown, these windings may be connected in series or parallel, as desired, for 125 or 250 volts. Each winding is in series with a field winding of an ordinary dynamometer-type a.-c. wattmeter. A secondary winding *S*, giving about 30 volts maximum, is connected to the moving element of the wattmeter. The resistance *R* is adjusted to give full-scale deflection of the wattmeter element when a sine-wave voltage of 125 or 250 volts is applied to the terminals of the instrument. The reading of the voltmeter is evidently proportional to the loss in the iron core of the instrument. This core is made of high- and low-loss iron in such proportions as to give a standard loss.

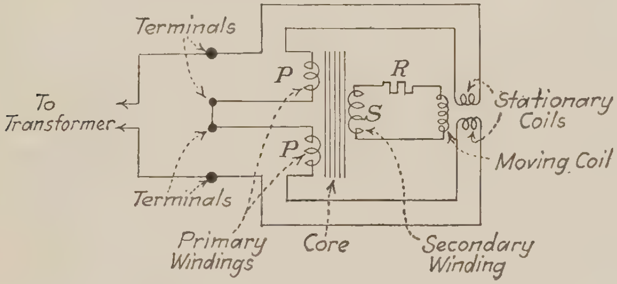

FIG. 190.—Iron loss voltmeter.

After completion, the instrument is connected to a sine-wave source of supply, and the scale calibrated in volts to agree with the voltage applied to the terminals. If, now, this instrument is connected to the secondary of a transformer which is excited from some convenient source, and the transformer secondary voltage is peaked, for instance, the iron-loss voltmeter will not read the r.m.s. volts, but will give a reading somewhat less, since its core does not have as high a maximum flux density as would be the case for a sine wave. At the same time and for the same reason, the maximum flux in the core of the transformer under test is low, and therefore the losses are lower than for a sine wave of voltage. Now, if the transformer applied voltage is raised until the iron-loss voltmeter reads correctly, according to the desired r.m.s. sine-wave voltage, the losses of the transformer under test will have the desired sine-wave losses provided the iron-loss voltmeter and the transformer have the same percentage of eddy losses.

It will be seen that the iron-loss-voltmeter reading is proportional not only to the loss in the meter core, but to the loss in the moving-coil circuit as well. The core material is made of laminations having very small eddy-current losses. The loss in the moving-coil circuit is similar to an eddy-current loss, since it is proportional to the square of the r.m.s. voltage. The effective eddy loss of the iron-loss voltmeter, therefore, is the sum of the core eddy loss and the moving-coil-circuit loss. The instrument is so proportioned that the eddy loss is from 25 to 30 per cent of the total loss, which agrees well with the percentage for the ordinary transformer.

Obviously, a different scale has to be used for each frequency, since the iron loss in the core varies approximately inversely as the 0.6 power of the frequency.

Since the loss in the iron-loss voltmeter is, for small transformers, an appreciable percentage of the transformer loss, for convenience a second scale is applied to the iron-loss voltmeter which gives the watt loss in the instrument for each reading. This enables the transformer tester to correct readily for instrument losses.

The iron-loss voltmeter makes possible the accurate testing of transformers for iron loss independent of the wave form of the supply. It has been used for many years for the commercial testing of transformers, both in the shop and in the field.

Types of A.-c. Test—Wattmeter Methods.—The most common and in general the most satisfactory methods of testing for a.-c. iron losses involve the use of a wattmeter. These methods of obtaining core-loss results may be classified as follows:

1. Ring test.
2. Epstein:
   a. Standard. *b.* Differential. *c.* Substitution.
3. Lloyd.
4. Robinson.
5. Three-phase ring (high induction).

Each of these types of test has its sphere of usefulness, as will be brought out in the following descriptions:

1. *Ring Test.*—If a ring sample of laminated steel is wound with a primary and secondary winding, the core loss may be tested as

shown by Fig. 191. The primary is connected to a source of alternating current through a wattmeter W and an auto-transformer T. The secondary is connected to the shunt circuit of the wattmeter and a voltmeter V. A frequency meter F is used to indicate the frequency of the supply circuit. For these connections, the reading of V is proportional to the maximum induction in the sample.

$$B_m = \frac{E \times l \times d \times 10^8}{4 \times ff \times N_2 \times f \times W}, \qquad (89)$$

where E is the r.m.s. volts;

l is the mean circumference of the ring in centimeters;
d is the density;
ff is the form factor of the voltage wave;
N_2 is the number of secondary turns;
f is the frequency in cycles per second;
W is the weight in grams.

The wattmeter gives the core loss plus the instrument losses in the voltmeter and the shunt circuit of the wattmeter. In order to obtain the true core loss, the instrument losses, as calculated from the r.m.s. volts and the voltmeter and wattmeter shunt resistances, must be subtracted from the wattmeter reading. The use of the secondary winding is desirable, because it eliminates any errors due to IR drop or I^2R losses in the primary.

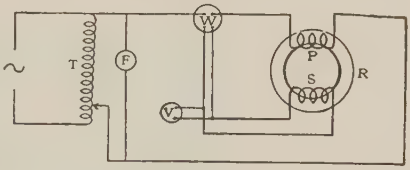

FIG. 191.—Connections for core loss test of laminated steel ring sample.

The ring test is subject to certain errors. These errors are due to the difference in circumference from the inner radius outward, the m.m.f. per unit length being greater toward the center. This was discussed in Chap. XVIII for the conditions of d.-c. testing. Under a.-c. conditions there exist the same or similar errors and, in addition, other errors due to the distortion of wave form for different annular sections. These effects have been dealt with theoretically and experimentally by Kennelly and Alger.[2] Under a.-c. conditions there is even more reason for keeping the relative radial width of punchings small than under d.-c. conditions.

As shown by the above formula, for reasonably accurate results, it is necessary that the induced voltage have practically a sine-wave form factor or, at least, that the form factor be known.

Methods of measuring and controlling the form factor will be discussed in connection with the Epstein test. The ring sample for a.-c. testing is used only in special cases, since it is difficult to wind and more material is wasted than for the Epstein test.

2. *a. Standard Epstein Method.*—The Epstein method is the standard method adopted by the American Society for Testing Materials (see Chap. XXII) and is very widely used in America and Europe. The connections are similar to those used for the ring test (see Fig. 191) the chief difference being that the sample now consists of four equal bundles of strips of sheet material arranged in a hollow square, as shown in Fig. 192. The strips are 50 by 3 centimeters ($19\frac{11}{16}$ by $1\frac{3}{16}$ inches) and weigh 10 kilograms. Each bundle is slipped into a solenoid, as indicated by the dotted lines. Each solenoid has two layers of wire. The outside layer is used as the primary and the inside layer as the secondary. The four primary coils are connected in series, as are also the secondary coils. Figure 193 shows one form of Epstein testing apparatus which is very convenient. After the

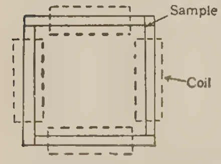

Fig. 192.—Arrangement of Epstein samples for core loss test.

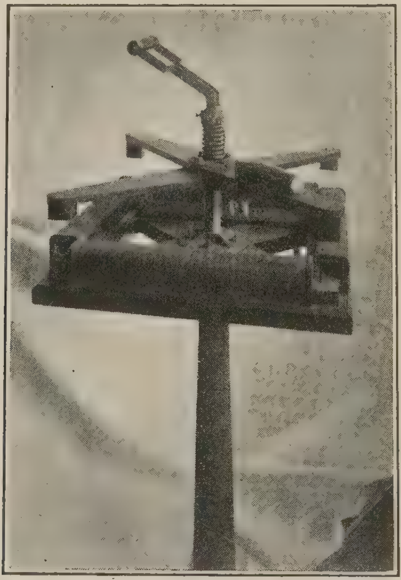

Fig. 193.—Epstein apparatus.

sample is placed in position in the coils, the handle at the top is thrown over, which clamps all four corners at once. The apparatus may be swung around on the pedestal to assist in the insertion and removal of the sample.

Since there is often a difference of 10 or 15 per cent between the loss of sheet material sheared parallel and that sheared at right angles to the direction of the grain, it is usually specified that one-half of the material shall be sheared one way, and one-half sheared the other way. For routine tests, in order to save the extra cost of material, it is usually satisfactory to use only a 5- instead of a 10-kilogram sample. Where many hundred samples a year are required and the material is worth 15 or 20 cents a kilogram, the saving is well worthwhile, since there is practically no decrease in the accuracy of testing if suitable instruments are used.

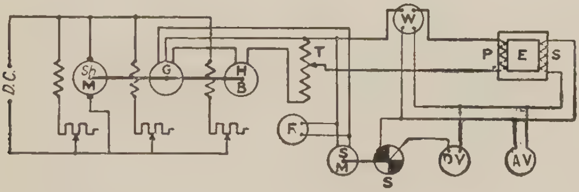

Fig. 194.—Simplified circuit for accurate laboratory method of core-loss test.

A satisfactory form of Epstein equipment for standardizing work, and routine also, if the expense is not too great, is that employed by the Research Department of the Westinghouse Electric and Mfg. Co. Figure 194 shows the diagram of connections. This is arranged to give a sine-wave form factor for the secondary voltage. The d.-c. motor *ShM* drives a three-phase a.-c. generator *G* and a harmonic booster *HB*, all three machines being on the same shaft. The booster *HB* generates a third harmonic and is in series with the generator *G*. This third harmonic may be introduced into the a.-c. circuit with any desired phase angle by rotating the field of the booster. Connected to the booster and generator is the autotransformer *T*, which supplies the Epstein apparatus *E* through the wattmeter *W*. The secondary of the Epstein apparatus is connected to an a.-c. voltmeter *AV*, a d.-c. voltmeter *DV*, and to the shunt circuit of the wattmeter. The d.-c. voltmeter is connected in series with a suppressor *S* driven by a synchronous motor *SM*. This synchronous motor, together with a frequency meter *F*, is connected to another phase of the generator.

The operation is as follows: The frequency is adjusted to 60 cycles by varying the field of the shunt motor, the voltage is adjusted by varying the field of the generator, and the form factor is adjusted by varying the field of the booster. The d.-c. voltmeter *DV* is a 2 to 1 double-scale instrument. It is connected to the low scale and read on the high, since every half wave is suppressed. When the form factor is correct, the ratio of the reading of *AV* to *DV* is 1.11, provided the phase of the suppressor is adjusted so that *DV* reads a maximum. The d.-c. voltmeter circuit is then opened and *AV* adjusted to the voltage value necessary to give a maximum induction in the sample of $B =$ 10,000 gausses. The wattmeter is then read. The instrument losses in the shunt circuit of the wattmeter and the a.-c. voltmeter are subtracted, the difference divided by the weight of the sample in kilograms, and the result is the loss in watts per kilogram for the sample. If the wattmeter has automatic compensation for the loss in its shunt circuit, only the instrument loss of the voltmeter needs to be subtracted. The formula for calculating the necessary secondary voltage is given in the above-mentioned American Society for Testing Materials test specifications. For a 10-kilogram sample and high-silicon material, the voltage is 106.6 and for low-silicon steel it is 103.8.

The above procedure requires considerable rather expensive apparatus and is somewhat complicated. It is not warranted except for standardization work and research investigations of high accuracy. As a consequence, several alternative arrangements have been devised to simplify the procedure for commercial testing. If the generator is of sufficient size and is carefully designed so as to give a sine wave of voltage, the harmonic booster and form-factor measuring apparatus may be omitted for tests at $B = 10{,}000$ gausses. If results are required at higher inductions, however, the exciting current of the sample will distort the voltage wave, due to the resistance and reactance in the primary circuit, thus giving erroneous results.

2. *b. Differential Methods.*—For the greatest simplicity, it is desired to have an apparatus which can be operated from a commercial a.-c. circuit. Several differential methods have been devised which accomplish this result. They make use of an

accurately standardized Epstein sample which is compared with the unknown by means of a special wattmeter.

One very successful device of this kind is that due to van Lonkhuyzen[3] and illustrated by Fig. 195. N is an Epstein apparatus containing a sample which has been standardized by some absolute method, and X is another Epstein apparatus which contains the unknown sample. The primary windings are M_N and M_X respectively, and the corresponding secondary windings are S_N and S_X. W_N and W_X are adjustable noninductive resistances in series with the secondary windings and the shunt circuits of a differential wattmeter, whose series coils are L_N and L_X. The supply voltage is connected to the two primary windings in parallel through the wattmeter series coils, and is adjusted until

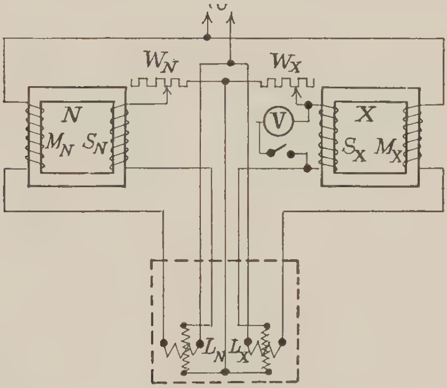

FIG. 195.—Van Lonkhuyzen differential Epstein apparatus.

the voltmeter V reads the required secondary voltage corresponding to the desired induction. V is then open-circuited, and W_X and W_N adjusted for a zero reading of the differential wattmeter. Then, there exists the relation,

$$\frac{\text{loss of } X}{\text{loss of } N} = \frac{W_X}{W_N}. \tag{90}$$

If W_N and W_X are calibrated in terms of the loss in the samples, W_N may be set corresponding to the loss in the standard sample, and then, when W_X is adjusted for a balance, the reading of W_X gives the loss of sample X directly. Errors due to fluctuating line voltage, frequency, form factor, and temperature are largely compensated for by this method. The chief disadvantage of the method is that a special wattmeter is required.

A somewhat similar device is that due to Augermann.[4] In his apparatus no secondary windings are used on the Epstein apparatus. One side of the line is connected to one end of each of the Epstein primary windings, and the other to the center point of the current winding of a wattmeter. The ends of the current coils of the wattmeter are connected to the other Epstein primary terminals. The shunt circuit of the wattmeter is connected across the terminals of one Epstein winding and a dummy resistance of equal amount is connected across the terminals of the other Epstein apparatus. The wattmeter reads the difference in loss of the two samples. Obviously, this method, while simpler, is not as accurate as that of van Lonkhuyzen, chiefly because differences in exciting current for the two samples will introduce appreciable errors.

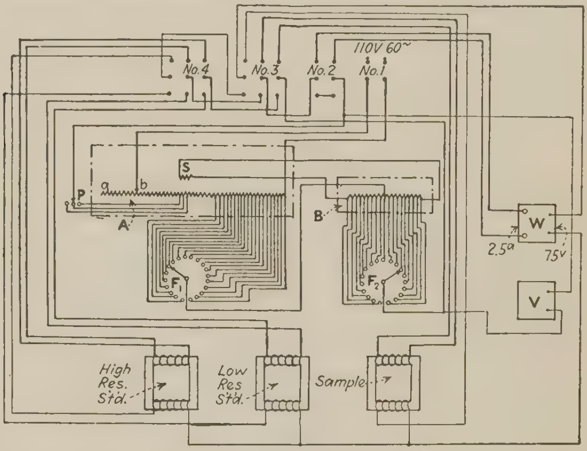

Fig. 196.—Detailed arrangement of substitution method for core loss testing.

2. c. *Substitution Methods.*—In order to obviate the necessity of using a special wattmeter, the following arrangement was devised and has been in successful use for some years for commercial Epstein testing. Two autotransformers with a number of regulating taps are the only special apparatus required. If an a.-c. generator with any reasonable wave form, the voltage of which may be varied, is available, even these may be dispensed with. Referring to Fig. 196, switch 1 connects the primary of the autotransformer *A* to a commercial 60-cycle, 110- or 220-volt line. If 220 volts are used, the line is connected to tap *a* instead of tap *b*. At one end of the transformer are a number of taps connected to

every other button of a field-rheostat face plate F_1. On the core of the transformer A is a little secondary winding of 3 turns which is connected to the terminals of a second autotransformer B. Taps from this second transformer are connected to a second face plate F_2. Specifications for the transformer windings are as follows:

Transformer A:
Total primary turns = 440.
Taps at 220, 315, 325, 335; also 420, 421–440.
E = 220 volts.
I = 30 amperes.
Frequency = 60 cycles.
Secondary turns = 3.
Transformer B:
Total turns = 20.
Taps at each turn.

Three Epstein sets are provided, one for the sample to be tested, one for a high-silicon standard, and one for a low-silicon standard. The standard samples are placed in their coils, wedged permanently in position, and impregnated. No clamping device is supplied for the standard samples. These standard samples are then calibrated for loss on a sine-wave supply of voltage as explained above. The wattmeter is a commercial, compensated, low power-factor instrument having a current range of 0 to 2.5 and 0 to 5, and a voltage range of 0 to 75 and 0 to 150. Any a.-c. voltmeter with suitable range may be used.

The operation of the apparatus is as follows: Switch 1 is closed, thus energizing the transformer. Switches 2 and 3 are closed down. Switch 2 is used simply to prevent an accident happening to the wattmeter in case there is a short-circuit in the apparatus, or in case switch 3 is closed on the Epstein apparatus without a sample in the coils. Switch 4 is then closed, either up or down depending on whether high-silicon or low-silicon material is being tested. Switch 2 is then thrown up, and the rheostat contacts F_1 and F_2 adjusted until the wattmeter reads the known loss of the standard sample. It will be noted that F_1 gives coarse adjustment and F_2 fine adjustment. If the correct voltage cannot be obtained, due to a large difference in the supply from normal, a still further range may be obtained by changing terminal P to one of the other taps. When the wattmeter reads the correct value, the voltmeter reading is noted. Switch 3 is then thrown up, voltmeter V adjusted to the same reading as before, and the wattmeter read. This gives the loss of the unknown sample. It should be noted that the voltmeter is connected to the primary side of the Epstein apparatus and that the only energy used from the secondary circuit is that necessary to supply the wattmeter shunt circuit. This is automatically subtracted from the wattmeter readings, since the wattmeter is compensated.

In order to save expense, a 5- instead of a 10-kilogram sample is often used for commercial work. The wattmeter has two scales, one for the 75- and one for the 150-volt connection. If the sample has a loss of, say, 3 watts per kilogram, the total loss will be 15 watts. This will be read directly on the low scale. If the reading is taken on the high scale and the decimal point shifted, however, the reading will be directly in watts per kilogram. It will be noted that the transformer connection used gives a little over 50 volts for the primary of the Epstein apparatus, instead of a little over 100 volts, as called for by the American Society for Testing Materials specifications. This is due to the fact that the half-weight sample is used, and so the applied voltage must be one-half.

It will be noted that changes in the supply voltage will not introduce errors, since the voltmeter is maintained at the proper value by moving the contacts F_1 and F_2. Variations in frequency will not introduce errors unless they occur between the time the standard sample is checked and the unknown is tested. A 1 per cent change in the frequency under these conditions will produce an error of about 0.6 per cent in the iron-loss reading. The frequency of large commercial power plants, however, is usually maintained fairly constant. If frequency changes are considerable, the errors may be reduced by checking often against the standard sample, or by using an iron-loss voltmeter for V.

The value of the form factor of the supply circuit is immaterial, provided it does not change between the time of checking the standard sample and testing the unknown. An appreciable change would occur only if the supply generator were changed or there were large changes in the reactive load in the near neighborhood. If such conditions do exist, the remedy is the same as for changes of frequency.

The fact that the voltmeter is on the primary circuit instead of the secondary will not introduce appreciable errors due to variations in permeability of the samples and reluctance of the air-gaps, since the primary windings have low resistance. It is because low resistance is essential in the primary circuit that autotransformers are used for controlling the voltage instead of variable resistances. If the additional expense is not a serious objection a somewhat more easily controlled circuit may be obtained by substituting an induction regulator for the autotransformers.

A moment's consideration will show that changes in the calibration of the meters produce no appreciable errors in the test results unless these errors are excessive. The only variable left is, then, the standard samples. Experience has shown that, when properly mounted, these samples do not change to any extent over long periods of time. One installation of this type has been in continuous service for about 8 years, during which time the meters have not been calibrated. The test results are as accurate as when the apparatus was first installed.

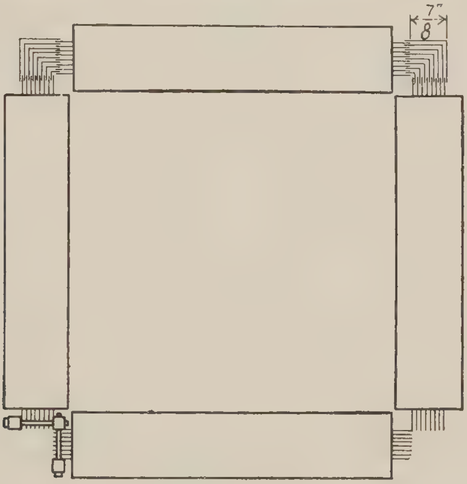

FIG. 197.—Lloyd core loss testing apparatus.

3. *Lloyd Method.*—Although the Epstein apparatus is the standard, it is subject to slight errors due to the type of magnetic circuit. The shape of the circuit and the buttjoints tend to produce leakage and nonuniform flux, thus introducing errors of possibly 2 or 3 per cent in the losses. Also, the effect of shearing the samples produces quite appreciably increased losses unless the material is annealed before testing.

M. G. Lloyd[5] undertook to overcome these disadvantages by means of a modified Epstein apparatus. The samples, which weigh only 2 pounds, consist of strips 10 by 2 inches (25.4 by 5 centimeters) and are placed on edge with specially formed corner pieces of known magnetic quality (see Fig. 197). This arrangement keeps the flux more nearly uniform throughout the sample and reduces the shearing effect by using a wider sample.

The Lloyd apparatus is not used anywhere nearly as extensively as the Epstein, for several reasons. It requires corrections for the corner pieces, and the selection of corner pieces which have somewhere near the magnetic quality of the material to be tested. More time is required to assemble the samples in the testing set. Finally, due to the small weight of sample, more sensitive instruments are required; commercial instruments being unsuitable.

4. *Robinson Apparatus.*—The Epstein and the Lloyd apparatus, in general, require a considerable quantity of material. A 5-kilogram Epstein sample of silicon steel will cost, including shearing, perhaps a dollar or more. When hundreds of samples per month are tested, this may be an appreciable item.

In order to reduce the weight of the sample required, some years ago L. T. Robinson,[6] devised an apparatus for determining the hysteresis loss by a low-frequency method which uses a sample weighing only about one pound. The sample consists of a single bundle of strips 10 by 0.5 inches, placed in a solenoid supplied with current having a frequency of about 10 cycles. The losses are measured by means of a sensitive wattmeter and corrections made for the small eddy-current losses. The flux, of course, is not uniform, but a correction factor is applied to take care of this condition. The apparatus is said to be accurate to plus or minus 5 per cent, which is not quite so good as the Epstein.

Unless the samples are re-annealed after punching, there may be a 20 per cent or more increase in loss due to punching or shearing strains, since the samples are so narrow. Again, in most applications the eddy losses are important, and for some classes of material may amount to nearly 50 per cent of the total at 60 cycles. A normal-frequency test giving the combined losses, in general, is more suitable than simply a determination of the hysteresis alone.

The saving in weight by the use of the Lloyd and the Robinson types of apparatus is of less moment than might at first appear, due to the fact that, because of the variability of commercial electrical sheet material, a test sample usually should consist of material taken from at least two full-sized sheets, and should be so chosen as to give an average of the whole. Since two or more sheets, weighing perhaps 15 or 20 pounds altogether, are to be spoiled anyway, there is little real gain in using the light-weight samples.

5. *Three-phase Ring.*—If an attempt is made to use any of these methods to obtain results at high inductions, it will be found difficult to obtain satisfactory data, due chiefly to the fact that the large exciting current with its high harmonics greatly distorts the induced-voltage wave, because of the inductance and resistance in the primary circuit. As a consequence, the form factor becomes quite different from the desired value. Nicholson[7] attempted to overcome this difficulty, partly at least, by using three identical ring samples provided with primary, secondary, and tertiary windings. The primary windings are connected in Y to a three-phase source of supply through wattmeter current coils. The secondary windings are also connected in Y to the shunt circuits of the wattmeters. The tertiary windings are connected in Δ to a generator giving a third harmonic of current. This tertiary circuit contains a wattmeter and, across its terminals, a voltmeter. The third harmonic voltage is so adjusted in phase and magnitude that the wattmeter in its circuit reads zero and the voltmeter a minimum. Under these conditions no power is supplied or absorbed by the tertiary circuit, the total losses being supplied and read from the primary circuit. Since the third harmonic is chiefly responsible for the distortion of the induced voltage, these distortions may be greatly reduced by supplying the necessary third harmonic of exciting current from a separate source. By this means it is possible to obtain satisfactory iron-loss results up to inductions of 20 kilogausses or more.

1. Effect of Wave Form upon the Iron Loss in Transformers, M. G. Lloyd, *Bur. of Standards Bul., Sci. Paper* 88, 4, vol. 4, May, 1908.

2. Magnetic Flux Distribution in Annular Steel Laminae, A. E. Kennelly and P. L. Alger, *Trans. A.I.E.E.*, p. 1113, December, 1917.

3. New Arrangement for Testing Sheet Iron, van Lonkhuyzen, *Elektrotechn. Z.*, vol. 33, pp. 531–534, May 23, 1912.

4. Measurement of Iron Loss by the Epstein Apparatus, Augermann, *Elektrotechn. Z.*, vol. 33, pp. 231–238, Mar. 7, 1912.

5. The Testing of Transformer Steel, M. G. Lloyd and J. S. Fisher, *Bur. of Standards Sci. Paper* 109; *Bul.* 5, p. 452, 1908–1909.

6. Commercial Testing of Sheet Iron for Hysteresis Loss, L. T. Robinson, *Proc. A.I.E.E.*, vol. 30, p. 741, 1911.

7. Magnetization of Iron at High Flux Densities with Alternating Current, J. S. Nicholson, *Jour. I.E.E.*, vol. 53, p. 248, February 1, 1915.

CHAPTER XXI

A.-C. TEST METHODS (*Continued*)

Bridge Methods.—For commercial and audio frequencies and for low inductions, a.-c. bridge methods for measuring effective permeability and core loss may be used to advantage. These methods are not very satisfactory at the higher inductions, due to the large variations in permeability with induction, and to the resulting distortions caused by these variations of permeability, since the calculations are based on the assumption of a sine wave of flux and current. These bridge methods are particularly useful when small samples only are available.

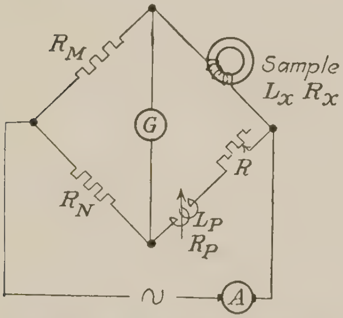

Fig. 198.—Maxwell bridge for measuring iron losses and effective permeability.

One of the simplest forms of bridge for this purpose is some modification of the Maxwell bridge (see Fig. 198). R_M and R_N are the two ratio arms of the bridge. The sample (shown as a ring) has an effective inductance L_X and an effective resistance R_X, and occupies the third arm of the bridge. The fourth arm contains a variable self-inductance having an inductance L_P, a resistance R_P and, in series, the variable resistance R. In case the sample has a lower resistance than the variable inductance, means are provided for shifting R to the sample arm of the bridge. The detector G may consist of a vibration galvanometer or d.-c. galvanometer with a synchronous or nearly synchronous contactor, or for audio frequencies a telephone receiver may be used. The bridge is balanced by varying R and the inductance until G indicates zero or a minimum.

Under these conditions,

$$R_X = \frac{R_M}{R_N}(R_P + R). \qquad (91)$$

$$L_X = L_P\frac{R_M}{R_N}. \qquad (92)$$

If $R_M = R_N$, the loss in the sample is,

$$W = (R_X - r)\left(\frac{I}{2}\right)^2, \tag{93}$$

where r is the resistance of the winding on the sample and I is the reading of the ammeter A. If R_M does not equal R_N, I must be suitably corrected according to the ratio of these two resistances.

The effective permeability may be determined from the following formula, assuming no air-leakage flux between the windings and the sample:

$$L = \frac{4\pi N^2 \mu A}{10^9 l}, \tag{94}$$

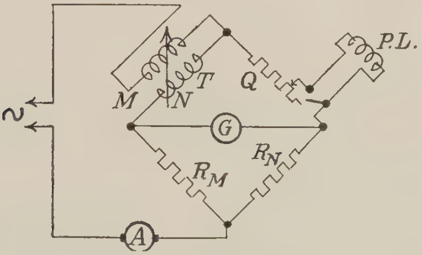

FIG. 199.—A.-c. bridge for measuring iron losses and effective permeability in the audio range.

where N is the number of turns on the sample;
A is the cross-section of the sample in square centimeters;
l is the mean length of the magnetic circuit of the sample in centimeters. For a ring, this reduces to:

$$L = \frac{4N^2 \mu A}{10^9 D}, \tag{95}$$

where D is the mean diameter of the ring in centimeters.

Another a.-c. bridge method described by Glazebrook[1] is shown by Fig. 199. P and L are the effective resistance and inductance of the sample. Q is a noninductive variable resistance. N and T are the inductance and resistance, respectively, of the other arm of the bridge. R_M and R_N are the noninductive ratio arms. M is a variable mutual inductance.

The operation is as follows: The bridge is first balanced with the sample short-circuited. The readings of M and Q under these conditions are designated as M_0 and Q_0. The sample is next inserted and the bridge again balanced. The M and Q

readings are then M_1 and Q_1. The effective inductance and resistance are calculated as follows:

$$L = (M_1 - M_0)\left(\frac{R_M + R_N}{R_N}\right). \tag{96}$$

$$P = Q_0 - Q_1 \tag{97}$$

If R_M and R_N are equal, the total iron loss in the sample is

$$W = (P - r)\left(\frac{I}{2}\right)^2. \tag{98}$$

This is similar to formula (93) for the previously described bridge. The effective permeability may be calculated from formula (95).

One of the best-known of the bridge methods for iron testing is that of Campbell.[2,3] The sample is provided with a primary and a secondary winding, N_1 and N_2 respectively (see Fig. 200). M is a variable mutual inductance; Q and R are variable resistances; A is an ammeter; and G is a vibration galvanometer for commercial frequencies or a telephone receiver for audio frequencies.

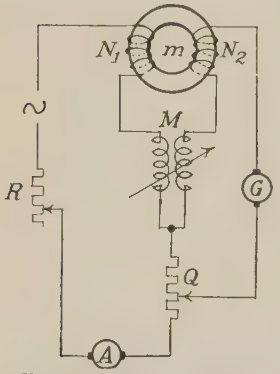

FIG. 200.—Campbell bridge for measuring iron losses and effective permeability.

The operation consists in applying a suitable a.-c. voltage as indicated, having as near a sine-wave shape as possible. If R is sufficiently large, the current also will have approximately a sine-wave shape. M and Q are then adjusted until G shows no deflection or until the telephone gives a minimum sound. Under these conditions,

$$W = \frac{N_1}{N^2} Q I^2; \tag{99}$$

where W is the loss in the sample in watts;

Q is the resistance of Q between the contact point and the inductance;

I is the reading of A in amperes.

The mutual inductance m of the sample including the air flux between the sample and the coils is equal to M when the balance is obtained.

$$M = m = 4 \times 10^9 \times N_1 \times N_2 \times \frac{(\mu A + A_1)}{D}; \tag{100}$$

where μ is the effective permeability of the sample

A is the section of the iron in cm.^{2}

A_1 is the area between the iron and the coils common to both windings;

D is the mean diameter of the ring sample in centimeters.

$$H_{\max} = \frac{0.4N_1I_1\sqrt{2}}{D} \text{ gilberts per centimeter} \tag{101}$$

$$M = m = \frac{N_2(A \times B_{\max} + A_1 \times H_{\max})}{I_1 \times 10^8}. \tag{102}$$

Formula 102 is convenient for adjusting the current for a desired value of $B_{\max}$. Good accuracy may be obtained with $H_{\max}$ values as low as 0.001 gilbert per centimeter. It will be noted that the resistance of the windings does not have to be known.

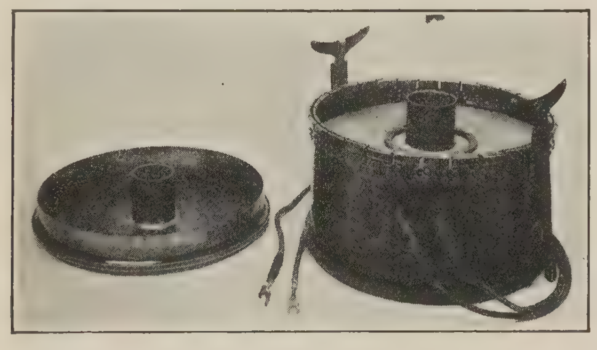

FIG. 201.—Kelsal permeameter.

Other bridge methods have been devised, but these are perhaps the simplest and most satisfactory for ordinary work. The first two methods apply when no secondary winding is available, as in the case of choke coils; and the third method is probably preferable when a suitable secondary winding is available or can be readily applied.

Kelsall Permeameters.—These permeameters[4,5] illustrate a novel method of measuring the magnetic properties of small rings for audio frequencies. Figure 201 shows a photograph of one of these permeameters adapted for room temperatures only, and Fig. 202 gives a cross-section of the permeameter.

The permeameter is divided into two compartments, one at the bottom for the primary winding and core, and the other at the top for the sample. The primary core consists of laminated rings of high-permeability material surrounded by a primary winding of 700 turns. The sample in ring form is located as indicated. A copper box with a central tube surrounds the whole, and, when the top cover is in position, the box furnishes a short-circuited secondary winding of 1 turn which links both the primary core and the ring-test sample. The current in this copper box supplies the m.m.f. for the test sample.

The primary winding is connected into one arm of a simple a.-c. inductance bridge, such as was described above, and the inductance measured without a sample in the permeameter, and with the cover off. This inductance value is called L_1. With the secondary closed (cover on), the inductance is again measured, giving L. Then, the inductance of the secondary transferred to the primary is:

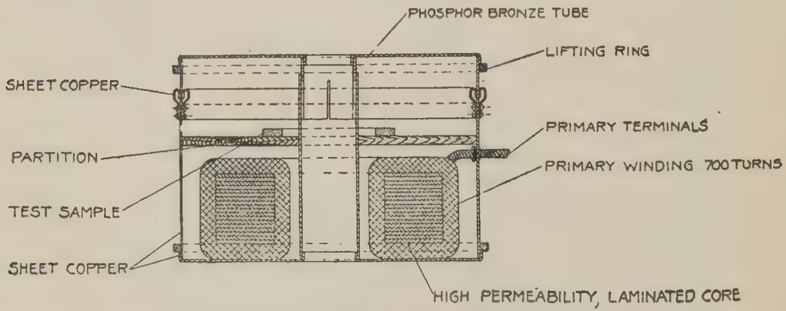

FIG. 202.—Section of Kelsall permeameter.

$$L_2 = \frac{L_1L}{L_1 - L}. \tag{103}$$

Now, if L_s is the value of L_2 with no test sample in position, and L_3 is the increase in L_2 when the test sample is inserted,

$$L_3 = \frac{LL_1}{L_1 - L} - L_s. \tag{104}$$

Then, as shown by Kelsall, the effective permeability of the test sample is:

$$\mu = \frac{L_3D10^9}{4N_p{}^2AK} + 1; \tag{105}$$

where D is the mean diameter of the ring in centimeters,
N_p is the number of turns in the primary winding;
A is the cross-section of the test sample in cm.^{2};

K is a factor equal to the ratio of the average m.m.f. to the m.m.f. at the mean radius of the test core (see Chap. XVIII, p. 295).

In order to determine H, the following formula is used;

$$H = \frac{2N_p(L_1 - L)I}{5L_1D} = \frac{FI}{D} \text{ gilberts per centimeter;} \tag{106}$$

$$F = \frac{2N_p(L_1 - L)}{5L_1}; \tag{107}$$

where I is the total current flowing through the primary.

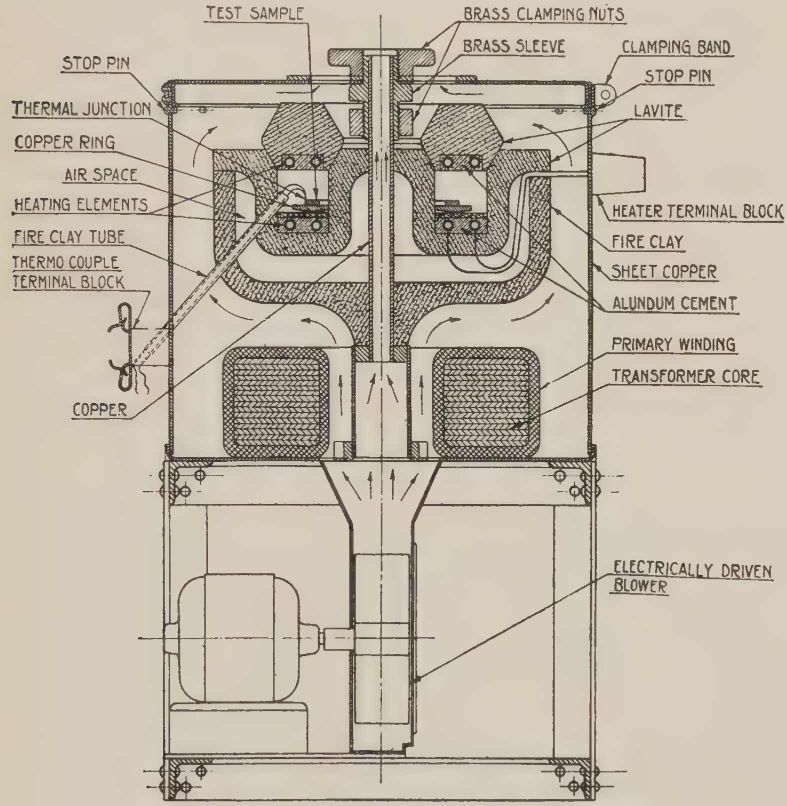

FIG. 203.—Kelsall permeameter for high temperatures.

For a given permeameter, the various constants are given by curves, thus making the actual calculations much simpler.

This permeameter, of course, is suitable only for small m.m.fs. It has the advantage that the ring samples may be very small and need not be wound with coils. Permeameters of this type have been used for testing whole spools of wire, as well as ring samples of solid or punched material.

Kelsall has modified this permeameter so that the samples may be heated to a temperature of 1000°C. or cooled by means of liquid air to −190°C. Figure 203 shows an outline drawing of this permeameter. The general construction and mode of operation are similar to those for the permeameter just described. In this case, however, the sample is enclosed in a lavite furnace lining having an annular space for the sample and a large copper ring below the sample, which assists in maintaining a uniform temperature. The heating is by means of resistance coils, as shown, wound noninductively. In order to keep the rest of the furnace cool, air is circulated by means of a blower. The method of making contact at the center and edges of the cover is somewhat different in order to avoid difficulties due to oxidation and consequent poor contact. The contact surfaces are clamped under appreciable pressure. The sample temperature is measured by means of a thermocouple welded to the sample.

With this apparatus, permeability values varying from approximately one up to many thousand may be readily measured.

A.-c. Potentiometer.—A very simple and satisfactory method of determining the true and apparent watt loss of a magnetic sample at low inductions is by means of an a.-c. potentiometer, particularly one of the Tinsley-Gall type.[6,7] This instrument consists of two distinct potentiometers, each supplied with alternating current of the same magnitude, but the current in one potentiometer is in quadrature with that in the other. For magnetic testing, it is desirable to supply the potentiometer from a two-phase phase-shifting transformer. Figure 204 shows a diagram of connections. The sample, which for convenience is shown in ring form, is provided with a primary and a secondary winding N_1 and N_2. A. c. of the desired frequency is supplied from a convenient source through a regulating transformer and series resistance. There is also in series a standard noninductive resistance R. The potentiometer is shown schematically below, the details being omitted. A represents one potentiometer and B the other. The two potentiometer currents are made equal by suitable adjusting resistances, not shown, and in quadrature by means of a mutual inductance and other adjustable resistances, not shown. These currents are of such a magnitude that the potentiometers read directly in volts. The phase-shifting transformer is supplied from the same source as the primary of the sample. The primary current in N_1 is first adjusted to some convenient value and switch S is thrown to the left, thus connecting the potentiometer to the secondary winding N_2. Potentiometer B is set to zero, and the phase-shifting transformer and potentiometer A then adjusted for zero reading of the vibration galvanometer VG. When this adjustment is completed, A gives the magnitude of the secondary voltage, and from it the induction in the sample may be calculated in the usual way, assuming a sine wave of voltage. This assumption is nearly true for low and moderate inductions, and approximately a sine-wave supply of current. This is far from true, however, for high inductions.

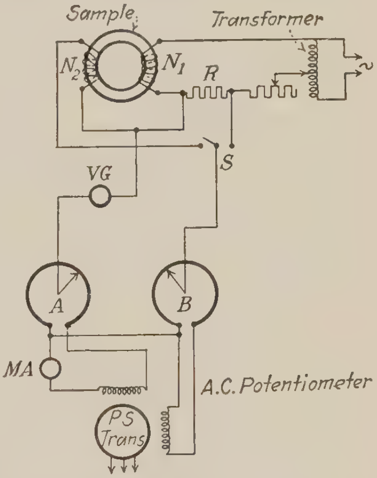

Fig. 204.—Connections for core loss and magnetizing-current measurements with a.-c. potentiometer.

Next, S is thrown to the right, which connects the potentiometer across the terminals of the shunt R. Potentiometers A and B are then adjusted for a vibration-galvanometer balance. The reading of A then is proportional to the loss component of the current in the primary winding, and the reading of B is proportional to the wattless or magnetizing component of the current. If $R = 1$ ohm, the readings of A and B are directly in amperes. This operation may be repeated for as many inductions as desired.

In series-transformer calculations these two components of current are used directly, so this makes a particularly desirable form of test. With a 10-pound sample, losses as low as 10^{-7} watts per pound have been measured with a fair degree of accuracy. This corresponds to an induction of only a few gausses.

This method is particularly suited to a study of the properties of audiotransformer punchings. The magnetic characteristics corresponding to a few gausses of induction, which is the normal operating condition for this material, may be readily obtained.

Also, if a very small ring sample of material consisting of a few grams only is available, the losses and effective permeability under a.-c. conditions may be readily determined approximately by this means.

High-frequency Test Methods.—It is impracticable to use a dynamometer type of wattmeter for the accurate measurement of iron losses at high audio and radio frequencies, due to the errors produced by inductance and capacity effects in the windings of the instrument. An electrostatic wattmeter might be used to avoid the inductance effects, but at high frequencies the capacity effects would introduce errors. There are other objections, also, to the electrostatic wattmeter which often makes it a rather undesirable instrument to use if anything else is available for the purpose. For these reasons, other methods have been devised, two of which will be described.

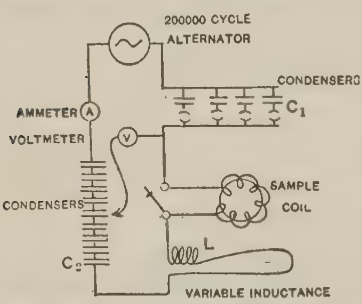

Fig. 205.—Alexanderson method of measuring high-frequency iron losses.

Alexanderson Method.—Some years ago Alexanderson[8] made iron-loss tests up to a frequency of 200,000 cycles per second, using a high-frequency alternator to supply the current. His circuits are shown by Fig. 205. The sample was in the form of a ring of soft-iron strap, and was provided with a single winding as indicated. Current from the high-frequency alternator passed through a hot-wire ammeter A, a series of one m.m.f. condensers C_2, a variable inductance L, the sample, and, finally, through a set of condensers C_1. A hot-wire voltmeter was connected between C_2 and one terminal of the sample as shown.

The method of test was as follows: The alternator was held at constant speed and the condenser C_1 adjusted until the current was a maximum as indicated by ammeter A. The voltmeter contact was then moved along C_2 until it indicated approximately a minimum. The final adjustment for a minimum was made by means of the variable inductance L. The voltmeter then read the resistance component of voltage across the variable inductance L and the ring. This multiplied by the current gave the total energy spent in the two inductances and in the portion of the condenser C_2 which was included up to the point of contact of the lead to V. The field of the alternator was then varied, and the voltage and current again noted. This was repeated for the desired range of inductions in the sample. With the sample short-circuited, L was again adjusted for a minimum reading of the voltmeter. This gave the loss in the variable inductance, leads, and condenser. Losses in the copper winding were also deducted and corrections made for the air flux between the winding and the sample. Finally, corrections were made for the losses in V.

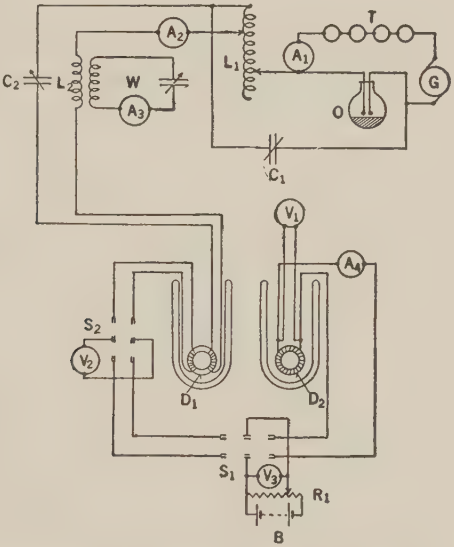

FIG. 206.—Double-calorimeter method of measuring high-frequency iron losses.

If desired, this same method could be used with a vacuum-tube or arc-oscillator supply of high-frequency current, provided the frequency was held sufficiently constant to give satisfactory resonance.

Double Calorimeter Method.—The particular method to be described has been used by the author[9] and is a modification of a somewhat similar method previously described by Nusbaum.[10] Figure 206 shows the circuits. The high-frequency supply was obtained from a tungsten-arc oscillator, but any other convenient source giving a sine-wave current would be satisfactory. Across the arc an oscillating circuit of paper condensers C_1 and a variable inductance L_1 was connected. Tapped across a portion of the inductance was a second-tuned circuit consisting of a variable condenser C_2, inductance L_2, the thermal ammeter A_2, and the primary winding of the sample D_1 to be tested. The object of this second circuit was to damp out any harmonics which might be generated by the oscillator. Inductively coupled with the inductance of the sample circuit was the wave meter W. The sample consisted of small enamelled ring punchings and was provided with a suitable primary and secondary winding as determined by the available ammeter and voltmeter. The secondary winding was connected to an electrostatic voltmeter of the quadrant-electrometer type. This voltmeter could be connected either to the sample secondary winding or to a calibrating circuit by means of the switches S_1 and S_2. When connected to the calibrating circuit, the voltage was read by means of the voltmeter V_3. When switch S_1 was thrown to the right, the heater coil D_2 was connected to the battery B. This heater coil was in intimate contact with some stampings exactly like those of D_1 and of the same weight. Thus there were two samples, one of which was heated by hysteresis and eddy-currents, and the other by the I^2R losses in the windings. The ease of escape of heat was about the same for the two samples. The losses in D_2 were measured by means of the voltmeter V_1 and the ammeter A_4. The calorimeters, each of which contained one of the samples, consisted of two Dewar flasks. These vacuum bottles were made at the same time and were practically identical as shown by cooling curves taken on them. The flasks were filled about two-thirds full of kerosene, and each was provided with a stirrer. The equality of temperatures of the calorimeters was determined by five pairs of copper-advance thermocouples connected differentially to a D'Arsonval galvanometer.

The method of operation was as follows: The oscillator was started and the capacity of the sample circuit adjusted approximately for the frequency desired, as determined by calculation. The wave-meter was set for the desired frequency, and the inductance and capacity of the arc circuit then adjusted for a maximum reading of the wave meter. The tap of the inductance L_1 was adjusted until the voltmeter V_2 read a value corresponding to the desired induction in the sample. At the same time that the high-frequency current was switched on, d.c. was applied to D_2, and varied until the differential-thermocouple galvanometer showed that the two calorimeters were heating at the same rate.

V_1 and A_4 were then read, and the loss in sample D_1 calculated. The thermal ammeter A_2 gave the exciting current and the induction was calculated from the usual formula, assuming that the induced voltage had a sine form. To obtain the actual voltages, the electrostatic voltmeter was connected to the battery circuit, R_1 adjusted until the electrostatic instrument read the same as it did on the a.-c. circuit, and the voltmeter V_3 was then read.

In order to eliminate any errors due to possible differences in the two calorimeters, the samples were interchanged at each induction and a second thermal balance obtained.

Hysteresis Meters.—A number of instruments have been developed for reading hysteresis values directly, based on the fact that, if a magnetizable specimen is placed in a revolving field or if the sample is revolved in a stationary field, a torque is developed which is proportional to the hysteresis loss per cycle. The Ewing hysteresis meter is typical.[11] The test sample consists of a rectangular specimen ⅝ by 3 inches, which is revolved between the poles of a permanent magnet, the latter being mounted on pivots and provided with a pointer. The motion of the magnet is restrained by means of a spring. The hysteresis loss in the sample produces a deflection of the magnet, and the deflection is proportional to the hysteresis loss per cycle, practically independent of the speed of rotation, provided the speed is sufficiently low, so that no appreciable eddy-currents are produced. The apparatus is calibrated by means of standard samples of known quality.

The Blondel apparatus is similar in operation to the Ewing, except that in this instrument the magnet is rotated and the deflection of the sample is noted.

In the Holden type of apparatus a ring sample is used with a revolving magnet. The sample is controlled by springs and is brought back to its initial position by means of a torsion head.

These instruments all have certain limitations which have caused them to become practically obsolete. As constructed, they take small samples which, unless annealed after punching, have considerably increased losses due to punching strains. Because of the shape of the samples, the flux is usually far from uniform. This makes an estimation of the effective flux density difficult. The flux distribution, moreover, changes with the permeability of the samples, thus making the hysteresis readings a function of the permeability. Due to the variability of commercial materials, such small samples cannot be made representative, thus requiring the preparation and testing of many samples, if accurate figures are to be obtained. Finally, for commercial work, the combined hysteresis and eddy losses are much more valuable than the hysteresis losses alone, and these instruments are not adapted for frequencies corresponding to 60 or even 25 cycles.

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3. Also, "Dictionary of Applied Physics," vol. II, p. 502.

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11. EWING, 3d ed., p. 380.

CHAPTER XXII

CHOICE OF METHODS—SEPARATION OF LOSSES—TEST AND MATERIALS SPECIFICATIONS

Choice of Methods.—Due to its simplicity, its reproducibility, and its very general adoption, the Epstein apparatus, especially as standardized by the American Society for Testing Materials, is probably the most satisfactory method to use for acceptance tests for electrical sheet. For routine testing, some form of substitution or differential Epstein test, as previously described, is most satisfactory, since such a test does not require a sine-wave voltage or accurately controlled frequency and does not need frequent calibration of the meters. If, however, research work is to be done, the simple substitution or differential apparatus will hardly suffice, especially if results at various inductions and frequencies are required. In that case a variable-speed generator is necessary, preferably with a harmonic booster and a means of measuring the form factor.

The standard Epstein apparatus has one characteristic which is considered objectionable by some; namely, that, due to the narrowness of the samples (3 centimeters), the hysteresis losses are quite appreciably affected by shearing strains unless the strips are annealed after the shearing operation. The test losses, therefore, to a slight extent at least, are affected by the sharpness of the shears. For this reason, some testers prefer a wider sample, though the use of such a sample may introduce other errors or sources of inconvenience which more than offset the advantages of the wider strips. The Lloyd apparatus offers one solution. While this method is used at the Bureau of Standards, it has not met with wide favor elsewhere, due probably to the complication of making corrections for the corner pieces.

The saving in material by the use of the Robinson or similar apparatus taking small samples is probably more than offset by the greater complication of the testing equipment, decreased accuracy, the effect of shearing on the narrow samples, and the fact that material from at least two sheets of steel should be used to give a good average for the lot.

For experimental work at high inductions, the three-phase ring method, when used with a sensitive polyphase wattmeter, may be recommended.

For radio-frequency tests the differential calorimeter method can be recommended as being simple and giving reproducible, reliable results, though a bridge method is quicker in general. The advantage of the calorimeter method is that there are fewer sources of possible error to be considered and eliminated.

For tests at low inductions where wave-form distortions are practically negligible, one of the previously described bridge methods or the a.-c. potentiometer method is satisfactory. The Kelsall permeameters may also be used under these conditions, but they are rather complicated and, except for certain special applications, perhaps, simpler methods are quite as satisfactory.

The so-called hysteresis meters are practically obsolete and, due to their inherent errors, are not to be recommended for general testing.

For permeability testing there is sometimes a choice between a.-c. and d.-c. methods for laminated materials. For small samples, approximately equal sensitivity can be obtained by the two methods. The speed of test can also be made about the same. For low inductions there is not much difference in accuracy. For high-induction values, however, the d.-c. methods are much superior as regards accuracy and ease of test.

The d.-c. permeameter methods cannot give eddy-loss results, therefore a.-c. methods must be used if total losses are required. If only hysteresis data are needed, either a.-c. or d.-c. methods may be used with approximately equal speed and accuracy, except that under a.-c. conditions, even with the material sufficiently laminated, so that there will be no skin effect, the hysteresis values often will be appreciably different for the two types of test, due to reasons which are at present somewhat obscure.

Separation of Losses.—The hysteresis and eddy-current losses may be separated by the following methods:

1. Two-frequency.
2. Two-form-factor.
3. Two-induction.
4. Alternating-and-ballistic.

1. The well-known *two-frequency method* consists in obtaining a.-c. core-loss data at two or more frequencies, say 30 and 60 cycles, for instance, dividing the results for a given induction by

the frequency, and plotting the watts per cycle against the frequency (see Fig. 207). The intercept on the vertical axis gives the hysteresis loss in watts per cycle, as indicated, and the eddy loss as indicated in watts per cycle for 60 cycles. This method may be applied to rotating machines, as well as to Epstein and similar samples.

2. The *two-form-factor method* consists in obtaining the core loss for two different form factors with the average volts (and therefore the hysteresis loss) held constant. The difference in the two losses is equal to the change in the eddy loss which, of course, is proportional to the square of the r.m.s. voltages, thus making it possible to determine the eddy losses. If loss values are obtained with a sine-wave form of the induced voltage E_s, and with a peaked voltage E_p, the following relations exist where W_s and W_p are the corresponding losses. The voltages are r.m.s. values.

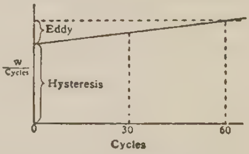

FIG. 207.—Separation of hysteresis and eddy-current losses.

$$W_s = W_h + W_{es};$$
$$W_p = W_h + W_{ep};$$

where W_h and W_e are the hysteresis and eddy losses, respectively.

$$W_p - W_s = W_{ep} - W_{es}$$

(increase in eddy loss due to peaked voltage).

$$W_{es} = \frac{W_p - W_s}{\left(\frac{E_p}{E_s}\right)^2 - 1}, \tag{108}$$

since the eddy loss is proportional to E^2. W_{es} is, of course, the eddy loss for the sine-wave voltage, and W_{ep} the corresponding value for the peaked voltage.

3. By measuring the losses at two inductions and assuming that the hysteresis loss varies as the 1.6 power of the induction, and the eddy loss as the square, it is possible to determine W_h and W_e from two simultaneous equations for a range of inductions of, perhaps, from 1 to 12 kilogausses. If one induction is one-half the other then,

$$W_h = \frac{4W_1 - W_2}{0.97}. \tag{109}$$

4. If desired, an a.-c. test may be made on a sample, then the hysteresis loss determined by means of a permeameter or some similar method. This hysteresis loss multiplied by the frequency of the a.-c. test gives the hysteresis loss for the a.-c. condition, from which and the total a.-c. loss, the eddy-current loss may be determined.

The two-frequency method is the simplest and is applicable to rotating machines and polyphase circuits as well as to the simpler cases. Care must be taken, however, to insure that the form factor is the same for the different frequencies. The two-form-factor method is perhaps the most accurate where suitable means are available for altering the form factor. The two-induction method is not as accurate as the two previous methods, since there are often quite appreciable departures from the 1.6-power and square laws even over the induction range mentioned. The fourth method is of use only in special cases when the others cannot be readily applied, and is not as reliable as the first two.

Test Specifications.—For the inspection of commercial magnetic materials for acceptance tests, a test specification is very desirable in order to insure that the test procedure shall follow some definite and well-established practice. Such a test specification is provided by the American Society for Testing Materials, a copy of which will be given later. Such a general specification which covers merely the method of sampling and test should be supplemented by a materials specification describing the particular qualities which are to be considered satisfactory and giving definite rejection limits. Such a specification may properly cover the following items (when referring to electrical sheet) which include not only the magnetic values, but all of the other important properties.

Magnetic properties:
    Core-loss limits (Epstein).
    Permeability.
    Aging.
Gage (Average values as calculated from the weight and dimensions with permissible variations and (or) micrometer values. The permissible variations should be greater for micrometer values due to unavoidable differences in gage in various portions of individual sheets.)
Standard sizes of sheets:
Condition of surface (scale).

Space factor (per cent solid).

Brittleness.

Stenciling.

Such a specification assumes that the material is annealed by the manufacturer before being sheared and tested.

If desired, the silicon content or the electrical resistivity may be specified, but it is not satisfactory to specify both the complete chemical composition and magnetic properties, since the two may be incompatible. If the material is to be shipped to the purchaser in the unannealed condition, the chemical composition should be specified instead of the magnetic properties, unless the supplier will agree to allow the purchaser to apply some definite heat-treatment to the samples before the magnetic properties are measured.

This materials specification may contain clauses modifying the standard (A.S.T.M.) test specification if desired, provided they are of minor importance. For instance, for most commercial work a 5- instead of a 10-kilogram Epstein sample is entirely satisfactory if mutually agreed upon by the manufacturer and purchaser. This means a considerable saving in the cost of sampling when large tonnage is involved.

Due to the difficulty involved in making uniform electrical sheet, it is desirable for a customer buying extensively to specify two or more grades of material having practically the same chemical composition or silicon content, the grades to be determined by the core loss or permeability, or both. The inferior grades, of course, would command a lower price. This enables the steel mills readily to dispose of most of their product, resulting in a reduction in price to the consumer and working no particular hardship, if the consumer uses judgment in the use of the various similar grades of material. A materials specification should not be too exacting, since otherwise it would simply result in an excessive cost of material to the customer. On the other hand, it should be sufficiently rigid to give occasional rejections, since, if it is too lenient, the manufacturer may become careless or may not make as good a product as he is capable of turning out.

A.S.T.M. MAGNETIC-TEST SPECIFICATIONS

Serial Designation: A 34-24T

Issued, 1924

A. Normal Induction and Hysteresis

I. DEFINITIONS

1. (*a*) *Normal Induction.*—The induction produced under a given magnetizing force in a substance which has been previously demagnetized and then subjected to a sufficient number of reversals of the given magnetizing force to bring it to a cyclic condition.

Both the induction and magnetizing force shall be expressed in terms of the c.g.s. electromagnetic units (gauss and gilbert per centimeter, respectively).

(*b*) *Magnetic Permeability.*—The ratio of the normal induction to the magnetizing force which produces it. Thus:

$$\text{Permeability} = \frac{\text{Gausses}}{\text{Gilberts per centimeter}}$$

(*c*) *Residual Induction.*—The magnetic induction which exists in a substance after the magnetizing force has been reduced to zero.

Note.—If the induction has been reduced from a point on the normal induction curve it is called the normal residual induction.

(*d*) *Coercive Force.*—The negative value of magnetizing force required to reduce the induction in a substance to zero.

Note.—If the induction has been reduced to zero from a point on the normal induction curve, the coercive force is called the normal coercive force.

II. METHODS OF TEST

2. The tests shall be made either by the ring method or by means of any permeameter having the required accuracy as specified below.

Specimens

3. Ring specimens shall not be welded, but shall be cut in a solid piece, and shall have a radial width of 3 centimeters ($1\frac{3}{16}$ inches). The mean diameter shall not be less than 30 centimeters ($11\frac{13}{16}$) inches.

In the preparation of samples of sheet steel, the dies or shears used shall be sharp.

4. (*a*) The cross-section of sheet steel samples shall be calculated from assumed or measured values of length, mass, and density.

Standard Densities

(*b*) For silicon and aluminum steels, a density of 7.7 shall be assumed where the silicon and aluminum content is 2 per cent or less† and a density of 7.5 shall be assumed where the silicon and aluminum content is over 2 per cent. For nickel steel, a density of 7.7 shall be assumed. For other alloys, a density corresponding to the actual measured or calculated value shall be used.

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† For silicon steel having a 2 per cent silicon content the electrical resistance is 2.6 ohms per meter gram.

III. ACCURACY

5. (*a*) Values of magnetizing force obtainable with ring specimens under the conditions specified above shall be considered to be correct within 1 per cent.

(*b*) Permeameters shall be considered satisfactory if they yield, either directly or with the aid of suitable corrections, values having the following accuracy: For normal induction, the values of magnetizing force corresponding to inductions up to 14,000 gausses shall be correct within 5 per cent; values of induction greater than 14,000 shall be correct within 2 per cent. For residual induction, values shall be correct within 2 per cent, and for coercive force, values shall be correct within 5 per cent.

IV. REFERENCE METHODS

6. In order to determine the accuracy of permeameters, they shall be checked by means of samples which have been standardized as follows:

(*a*) For use with material having a maximum permeability not exceeding 10,000, the standard samples may be calibrated by the Burrows compensated double-yoke method having magnetizing coils not less than 20.3 centimeters (8 inches) in length. The ratio of the area of the test coil to that of the specimen shall be such that the air correction factor shall not be greater than three. This air correction may be applied by calculation or eliminated by means of an adjustable mutual inductance having its primary connected in series with the main permeameter magnetizing winding and its secondary in series with the main test coil. This mutual inductance shall be set to such a value that the flux in the space between the sample and the test coil shall be automatically compensated for.

(*b*) For material having a maximum permeability exceeding 10,000, an elongated ring or link-shaped sample having parallel sides of substantially equal cross-sections shall be used. These shall be calibrated by winding with uniformly distributed primary and secondary windings and testing ballistically like a ring sample. This type of sample may also be used for checking permeameters for use with the lower permeability material instead of the method described in paragraph (*a*).

(*c*) For material to be tested at magnetizing forces exceeding 200 gilberts per centimeter, the modified isthmus method described in the U. S. Bureau of Standards *Scientific Papers Nos.* 361 and 383 shall be used.

7. Care must be exercised in all cases that the standardized samples are magnetically homogeneous and clamped so as to be free from mechanical strain.

V. STANDARD DATA

8. (*a*) The standard normal induction data for all magnetic materials shall consist of the values of magnetizing force corresponding to inductions of

2000, 4000, 6000, 8000, 10,000, 12,000, 14,000, 16,000, 18,000, and 20,000 gausses.

(*b*) Residual induction and coercive force values for sheet steel and materials of the type used for electromagnet cores shall be determined from a normal induction of 10,000 gausses.

(*c*) For permanent-magnet steel, the normal induction, residual induction, and coercive force shall be determined from a maximum magnetizing force of 200 gilberts per centimeter, unless the maximum permeability is less than 100, in which case the maximum magnetizing force shall be not less than two and one-half times the value of magnetizing force at which this maximum occurs and shall be some multiple of 200. Samples of magnet steel shall be hardened previous to testing in accordance with best metallurgical practice for the steel in question.

B. Core Loss

VI. DEFINITIONS

9. (*a*) *Core Loss.*—The power consumption in electrical sheet steel when subjected to an alternating magnetization.

(*b*) *Standard Core Loss.*—The total power in watts consumed in each kilogram of material at a temperature of 25°C. when subjected to a harmonically varying induction having a maximum of 10,000 gausses and a frequency of 60 cycles per second, when measured as specified below. It is represented by the symbol $W_{10/60}$.

(*c*) *Aging Coefficient.*—The percentage change in the standard core loss after continued heating at 100°C. for 600 hours.

VII. PROCEDURE

10. The standard core loss shall be measured under the following conditions:

(*a*) The magnetic circuit shall consist of 10 kilograms (22 pounds) of the test material, cut with a sharp shear into strips 50 centimeters (19$\frac{11}{16}$ inches) in length and 3 centimeters (1$\frac{3}{16}$ inches) in width, one-half parallel and one-half at right angles to the direction of rolling, made up into four equal bundles, two containing material parallel and two containing material at right angles to the direction of rolling, and finally built into the four sides of a square with buttjoints and opposite sides consisting of material cut in the same manner. No insulation other than the natural scale of the material (except in the case of scale-free material) shall be used between laminations, but the corner joints may be separated by tough paper 0.1 millimeters (0.004 inches) in thickness.

(*b*) The magnetizing winding shall consist of four solenoids surrounding the four sides of the magnetic circuit and joined in series. A secondary coil shall be used for energizing the voltmeter and the potential coil of the wattmeter.

These solenoids shall be wound on a form of any nonmagnetic nonconducting material of the following dimensions:

Inside cross-section	4 by 4 centimeters
Thickness of wall	not over 0.3 centimeter
Winding length	42 centimeters

The primary winding on each solenoid shall consist of 150 turns of copper wire uniformly wound over the 42-centimeter length. The total resistance of the magnetizing winding shall be between 0.3 and 0.5 ohm. The secondary winding of 150 turns of copper wire on each solenoid shall be similarly wound beneath the primary winding. Its resistance shall not exceed 1 ohm.

(*c*) A voltmeter and the voltage coil of a wattmeter shall be connected in parallel to the terminals of the secondary winding of the apparatus. The current coil of the wattmeter shall be connected in series with the primary winding.

(*d*) An electromotive force having a wave form approximating a sine curve shall be applied to the primary winding and adjusted until the voltage of the secondary circuit is given by the equation:

$$E = \frac{4fNnBM}{4lD10^8}$$

in which

f = form factor of primary e.m.f........ = 1.11 for sine wave;
N = number of secondary turns.......... = 600;
n = number of cycles per second........ = 60;
B = maximum induction................ = 10,000;
M = total mass in grams................ = 10,000;
l = length of strips in centimeters....... = 50;
D = density.......................... = $\begin{cases} 7.5 \text{ for high-resistance steel;} \\ 7.7 \text{ for low-resistance steel;} \end{cases}$
E = $\begin{cases} 106.6 \text{ volts for high-resistance steel for sine voltage;} \\ 103.8 \text{ volts for low-resistance steel for sine voltage.} \end{cases}$

The form factor of the applied electromotive force shall not depart more than 1 per cent from the value of 1.11. As an alternative to the use of a sine wave, the correct value of the voltage may be determined by applying it to an Epstein apparatus containing a sample which has been standardized by means of a sine-wave electromotive force. The wattmeter is brought to the correct reading for the standard sample. The corresponding voltage is the correct one to use.

Standard Densities

11. For silicon and aluminum steels, a density of 7.7 shall be assumed where the silicon and aluminum content is 2 per cent or less* and a density of 7.5 shall be assumed where the silicon and aluminum content is over 2 per cent. For other alloys, a density corresponding to the actual measured or calculated value shall be used.

12. The wattmeter gives the power consumed in the iron and the secondary circuit. The loss in the secondary circuit is given in terms of the total resistance and voltage. Subtracting this correction term from the total power gives the net power consumed in the steel as hysteresis and eddy-current loss. Dividing this value by 10 gives the core loss in watts per kilogram.

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* For silicon steel having a 2 per cent silicon content, the electrical resistance is 2.6 ohms per meter gram.

Sampling

13. The core-loss material shall be cut from two or more sheets taken at random from the shipment. The strips should be distributed symmetrically over the sheet, as nearly as may be practicable (see Fig. 208).

It is recommended that a test sample shall represent not more than 5000 kilograms (11,000 pounds).

14. (*a*) Cut the test material into strips 3 by 50 centimeters as indicated in Section 13.

(*b*) Place on the balance a pile of strips weighing 2.5 kilograms. Add a second pile of the same kind, bringing the weight up to 5 kilograms. In each case the weight is taken to the nearest strip. Add in succession two piles of 2.5 kilograms each, of the other kind of strips, bringing the weight up to 7.5 kilograms and 10 kilograms, respectively.

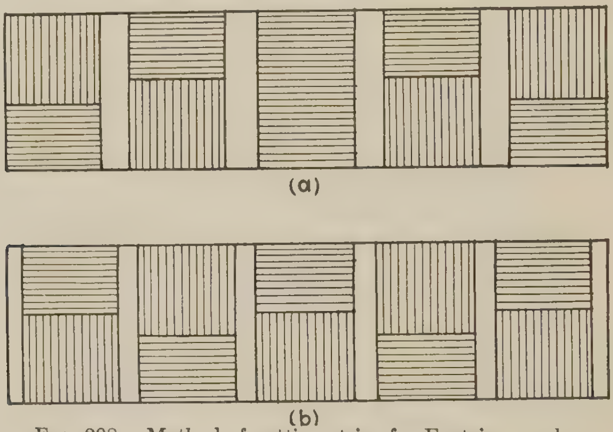

FIG. 208.—Method of cutting strips for Epstein samples.

(*c*) Secure each bundle by string or tape (not wire) and insert in the apparatus as indicated.

(*d*) Apply the alternating voltage to the primary coil and tap the joints together until the current has a minimum value, as shown by an ammeter in series. Then clamp the corners firmly by some suitable device.

(*e*) Shunt the ammeter and adjust the primary current until the voltmeter indicates the proper value. This adjustment may be made by an autotransformer, by varying the field of the alternator, or by both, but not by the insertion of resistance or inductance in the primary circuit. Simultaneously, the frequency must be adjusted to 60 cycles.

(*f*) Read the wattmeter.

(*g*) *Calculations.*—Subtract from the wattmeter reading the instrument losses, which will be constant for any set of instruments and voltage, and divide by 10. The result is the standard core loss.

NOTE.—If desired a 5-kilogram sample may be used for routine acceptance tests, provided it is cut from at least two sheets, except in case of a dispute between the manufacturer and purchaser, when the 10-kilogram sample shall be used.

PART III

COMMERCIAL APPLICATIONS

CHAPTER XXIII

INTRODUCTORY AND CORE LOSSES IN TRANSFORMERS

A knowledge of the properties of magnetic materials is of value chiefly in that it enables one to predict more or less accurately the operating characteristics of a piece of apparatus using a magnetized core. A knowledge of methods of magnetic testing enables one to readily insure that none but suitable magnetic materials go into a given piece of apparatus, as pointed out in detail in Chap. XIII. In the completed apparatus, however, there are almost always some more or less uncertain factors which complicate the problem of predetermining the performance, making it necessary, in general, to measure the core loss of a completed transformer or motor, for instance, to insure that it is within the expected limits. Sometimes, it will have unexpectedly low losses, but more often the losses will be unexpectedly high, due to factors in the design or construction which have been neglected. Again, a material which may be entirely suitable for the core of one type of electrical apparatus may be altogether unsuitable for another. Or, though several kinds of electrical sheet may be used to give practically identical performance, assuming suitable modifications in design for each kind of steel, some will be more suitable than others from a cost standpoint. Often, it will be preferable to use a poorer grade of electrical sheet and more of it, for certain types of apparatus, because of the price difference between various grades. An effort will be made to point out in a general way the cause of extra iron losses in electrical apparatus and discuss the chief factors which govern the choice of materials for the cores.

Extra Losses in Transformers.—In the calculation of core losses in transformers, it is customary to determine the total average flux from the calculated induced voltage and to assume that the flux is uniformly distributed over all sections of the core; namely, the flux density B is equal to $\frac{\phi}{A}$, where ϕ is the total flux and A is the core cross-section. If the core varies in section, as is often the case, two or more flux densities are calculated. This assumption of uniform flux density over a given cross-section would be approximately correct only in the case of very narrow long cores. In actual transformers, the cores are usually rectangular in shape and fairly short with reference to the width of core. The inner flux paths around the coils are, therefore, shorter than the outer flux paths. This produces a nonuniform flux tending to cause larger losses than if the flux were uniformly distributed, since the losses go up as a power of the induction greater than one; namely, about as the 1.7 power for commercial transformer material operating at inductions below 14 kilogausses. At inductions below the point of maximum permeability (up to from 6 to 10 kilogausses), moreover, the permeability increases with increasing flux density, thus increasing the nonuniform distribution of flux. Beyond the point of maximum permeability, the decrease in permeability with increasing flux density tends to produce a more uniform flux density over the core section than would be the case for constant permeability. For the case of increased flux density toward the inner portions of the magnetic circuit, of course, there may be little increase in core losses, due to the fact that a smaller volume of iron is subjected to the high flux density due to the shorter length of magnetic path. When, however, due to the decreased permeability at high inductions, the flux is forced toward the longer paths, the losses may be quite appreciably increased.

There is another factor, as shown by Kennelly and Alger,[1] which may appreciably increase the losses. Due to the same variations in permeability for different inductions and therefore for different flux paths, even though the induced voltage and therefore the mean flux have approximately a sine form, the flux in different belts may vary considerably from a sine shape. As a consequence, the hysteresis and eddy losses may be increased over what would be the case for a sine flux in all sections of the core. The reluctance of the joints at the corners of the core will tend to reduce this and the previously mentioned effects.

Another common cause of increased core losses in transformers over those which normally would be expected is that of leakage fluxes into the end frames, T-bars, and tanks, Although these leakage fluxes may not be very large, nevertheless, due to the fact that they penetrate solid material, sometimes of considerable thickness, they may produce quite appreciable hysteresis and eddy losses, especially if the core inductions are fairly high.

As has been pointed out in Chap. XI, these leakage fluxes may be of higher frequency than the fundamental in the case of three-phase core-type transformers, thus augmenting the difficulty.

Again, imperfect insulation between laminations, such as may be produced by burrs, for instance, can cause very considerably increased eddy losses. If certain sections of the laminations are less well insulated than others, the eddy-currents may produce a nonuniform distribution of flux which will result in an increase in hysteresis as well as in eddy losses. In this connection it should be mentioned that all bolts should be insulated from the core and should be so arranged that an electrical circuit which is cut by flux is not formed.

In the case of heavy-current transformers, particularly those used for electric furnace work, eddy losses, caused by leakage fluxes, may be produced in the copper conductors. These may appear as core losses, but in general they are a function of the secondary current and therefore would appear as load losses.

If the laminations are not flat, bending strains will be introduced after the laminations are assembled, thus often quite appreciably increasing the hysteresis losses.

There is one indirect cause of excess core losses which may be of considerable magnitude, especially in the case of small transformers where the assembly pressures are low. Due to poor processing of the core material, the space factor may be low, thus resulting in a decreased amount of core material being introduced into the transformer and a consequent increase in core loss. Also, if the design inductions are high there will be a large increase in exciting current over the expected value. This poor space factor may result from wavy sheets, burrs, poorly applied enamel or paper, or excessive scale (especially in the case of high-silicon sheet) due to improper rolling or heat-treatment. It may even happen, sometimes, that due to carelessness alone sufficient iron is not built into the coils. To obviate this difficulty, the correct amount of iron as given by calculation should be weighed out, and if it will not go into the allotted space an investigation should be made to determine and remove the cause.

From these various causes, the core losses in transformers usually will be quite appreciably higher than indicated by tests on Epstein samples taken from the core material. On the average, this difference may be pehaps 15 per cent, becoming less for transformers operating at lower inductions than normal, and more for high-induction transformers. Three-phase transformers, in general, will have a larger percentage of increased losses due to the above-mentioned causes than is the case for single-phase transformers.

Core Materials for Transformers.—In general, the lower the core losses of a material the higher the price. The cost of a high-grade 4 per cent silicon transformer steel may be double that of a low-silicon dynamo steel. The difference in core losses is also about two to one. Nevertheless, a large tonnage of both kinds of material is used for electrical apparatus. Most of the high-silicon steel, however, goes into transformers while most of the low-silicon material goes into rotating apparatus.

For distribution transformers, which have a comparatively poor load factor, and which are on the line 24 hours a day, thus being subjected to normal iron losses regardless of load, a very low-loss silicon steel averaging about 0.014 inch thick is generally used. In order to keep the losses and exciting current low, a fairly moderate induction is common, varying from 10 to 14 kilo-gausses (net section).

For power transformers, a somewhat higher loss material may be used, since the load factor is higher and 24-hour service is often not required. Much high-grade 4 per cent silicon steel is employed, however, even for power transformers. For self-cooled transformers, the low-loss material will often make possible the use of smaller tanks and less radiating surface, even though the higher efficiency is not demanded; namely, sometimes the extra cost of the core material is less than the extra cost of tank and radiators. A considerable quantity of medium-silicon steel (2 to 3 per cent silicon) is found in power transformers, since this often gives the most economical design.

In the case of 25-cycle transformers, it generally is economical to use a low-silicon sheet, since at the lower frequencies the hysteresis and eddy losses are not so high per unit volume of core material. Also, for the most efficient design, the core inductions are generally higher for 25-cycle transformers. In order to keep down the exciting current under these conditions, a low-silicon steel is preferable, since its high-induction permeability is higher than for the 4 per cent material.

Induction regulators usually use a high-grade 4 per cent silicon steel, since their service is similar to that of distribution transformers.

Auto-starting transformers for motors may use a high-loss core material, since they are on the line for a very short time and copper losses are the important factor.

Voltage transformers, operating at an induction of perhaps 10 kilogausses, use high-quality 4 per cent silicon core material, since high permeability at moderate inductions and low core losses are very desirable in order to produce small ratio and phase-angle errors.

Current transformers operate at low inductions; namely, an average of 1 kilogauss, or sometimes even considerably less. The hysteresis and eddy losses at low inductions must be low, and the permeability high, in order to give good performance. This is especially true for through-type transformers, since the ampere-turns are limited. As a consequence, the very best grade of electrical sheet is required. In the past 4 per cent silicon steel has been used, but some of the nickel-alloy sheets show promise in this connection. It recently has been shown that, a 50 per cent nickel-iron alloy properly heat-treated,[2] makes it possible to reduce the phase-angle and the uncompensated ratio errors for through-type transformers to about one-third of those obtained with a high-quality, 4 per cent silicon steel. This is due to the fact that for 50 per cent nickel iron the low-induction permeability is much higher and the hysteresis loss is much less than for silicon steel. The initial permeability is approximately 3000 for the former, and considerably under 1000 for the latter. As shown by Agnew,[3] the performance of current transformers (at least when flux leakage is negligible as is the case for through-type transformers) can be predicted quite accurately from the magnetic characteristics of the core material. These new current transformers should be very useful when it is necessary to measure large blocks of power quite accurately.

Material for audio transformer cores should have much the same characteristics as for current transformers, except that in the case of the audio-frequency transformers the average inductions are nearer 1 gauss than 1 kilogauss. For this application the initial permeability becomes a factor of considerable importance. The low-frequency performance of an audio transformer is largely a function of the core material. For the higher frequencies, the performance is practically independent of the quality of the core material, but is a function of the nature of the windings. From 60 to 200 cycles, the quality of the core material is of considerable importance; above 500 cycles, the core material has very little influence. For music such as given by the organ, transformers with high-grade core material are essential for faithful reproduction. For the same size of core it has been found that the 60-cycle amplification ratio of an ordinary audio-frequency transformer may be increased from two to three times by the use of a core of 50 per cent nickel iron, when substituted for the ordinary silicon-steel core. As far as the core is concerned, equivalent values can be obtained by using more of the silicon core material but this results in a much larger transformer than for the nickel alloy.

The nickel-iron alloys, of course, cost more, but the increased quality of performance will often more than compensate for the increased cost, both in the case of instrument transformers and transformers for radio purposes.

There are, then, three main factors to consider in choosing a core material for transformers—core loss, permeability, and cost. A transformer design is always a compromise in which the best balance possible has to be chosen. These different factors assume different degrees of importance depending on the application, and no general rule can be laid down which will fit all cases.

1. Magnetic Flux Distribution in Annular Steel Laminae, A. E. Kennelly and P. L. Alger, *Trans. A.I.E.E.*, vol. XXXVI, p. 1113, 1917.

2. Current Transformers with Nickel-iron Cores, Thomas Spooner, *Jour. A.I.E.E.*, p. 540, June, 1926.

3. A Study of the Current Transformer with Particular Reference to Core Losses, P. G. Agnew, *Bur. of Standards Bul.*, vol. 7, p. 423, 1911.

CHAPTER XXIV

CORE LOSSES IN ROTATING MACHINES

If the inductions in the cores and teeth of a rotating machine are calculated from the total flux per pole and the average cross-sections of the various parts of the magnetic circuits, and if the volumes of the magnetic circuits are multiplied by the fundamental-frequency hysteresis and eddy losses per unit volume corresponding to the given inductions as determined from samples of the core material, the calculated core loss for the machine, in general, would be very much less than the true core loss. Sometimes the ratio of the losses calculated in this manner to the true core losses is as small as one to three and more often than not less than one to two. While the causes of these extra losses have been known in a general way for a long time, it is only recently that a reasonably reliable quantitative estimate of their magnitude could be made from fundamental considerations. In the past it has been the custom to calculate the simple fundamental-frequency losses in the cores and teeth, and estimate the extra losses from empirical data obtained by test on similar machines. This is probably the most satisfactory method for standard types of apparatus, but it fails for radically new types of machines and gives no indication of how to reduce the extra losses.

It is customary, in general, to measure the no-load core losses of a machine and assume that they are approximately the same under load conditions. This is probably approximately true for the normal fundamental-frequency losses, but the extra losses are often considerably changed by the load conditions. Due to the difficulties of measurement, little is known at present concerning these additional or stray losses, as they are sometimes called. In general, it is possible to take them into account only by means of empirical constants.

Analysis of Core Losses.—A detailed analysis of the core losses in rotating machines, even confined to the present published knowledge, would fill a book. Such an analysis may be briefly outlined, however, with considerable profit, in that the nature and complexity of the problem may be shown and the various types of loss which are of importance in the more common types of rotating machines may be pointed out. The following outline is an extension and modification of one given by Alger and Eksergian.[1] This outline is not confined to induction motors, but covers all major types of rotating machines. Those copper losses are included which appear as if they were no-load core losses by the ordinary methods of test.

A. Legitimate Core Losses:
  1. Fundamental-frequency iron losses:
    a. In the core.
    b. In the teeth.
  2. Fundamental-frequency leakage losses:
    a. Slot-leakage flux losses (copper eddy-current):
      (1) Parallel flux.
      (2) Transverse flux.
    b. Losses in metal wedges or bands.
    c. Losses in end plates, frames, etc.
  3. Tooth-frequency iron losses:
    a. In the core.
    b. In the teeth.
  4. Surface, or pole-face, losses.
  5. Tooth-frequency copper losses due to circulating currents.
  6. Tooth-frequency leakage losses.
  7. Losses due to nonsinusoidal current distribution:
    a. Losses due to spreading of the main flux just back of the teeth.
    b. Losses due to harmonics other than tooth harmonics.

B. Illegitimate Core Losses Caused by Imperfections in Manufacture:
  1. Due to bending.
  2. Due to punching.
  3. Due to slot filing.
  4. Due to pressure.
  5. Due to poor space factor.

C. Stray Iron Losses:
  1. Nonsymmetrical distribution of pole flux due to armature reaction.
  2. Copper eddy-current losses.

3. Losses in end bells, etc. due to armature-coil-leakage fluxes.
4. Increased surface and tooth-pulsation losses.

It is now evident why the busy machine designer resorts to empirical curves for most of his core-loss calculations. It would be impossible to spend the time to calculate the individual losses for all designs even though satisfactory methods were available.

This analysis will now be considered in some detail with the object of determining the relative importance of the various types of loss as a function of the different types of machines.

A. Legitimate Core Losses.—1. *a.* An alternating uniform sine-flux distribution in the core is usually assumed when, as a matter of fact, it is generally somewhat and often quite different from a sine form. It is often of rotating ellipsoidal form, moreover, instead of being alternating. Alger and Eksergian[1] have given a very able analysis of the increased losses to be expected due to an ellipsoidal, nonuniform-flux distribution as compared with a uniform alternating one. The increased losses are particularly marked in the case of a deep core and a large number of poles.

1. *b.* Usually, the slot sides are made parallel, thus causing rotating-machine teeth to be trapezoidal in form. This produces nonuniform induction in the teeth. A very rough approximation of the equivalent average value of flux in the teeth is usually made. This is often based on the assumption that the hysteresis losses vary as the 1.6 power of the induction. As a matter of fact, the ratio of variation is more nearly the square or the cube at maximum tooth inductions. The most common assumption and one which is usually satisfactory is to base the induction on a tooth cross-section one-third of the distance from the narrowest section.

2. *a.* (1) By parallel-slot-leakage flux is meant that flux which starts down the slot nearly parallel to the slot sides. It results in eddy losses in the copper which can be practically eliminated by proper lamination of the windings and is subject to more or less accurate calculation.

2. *a.* (2) By transverse-leakage flux is meant the flux which goes across the slot; as, for instance, when a slot passes a field-pole tip. Various approximate formulas have been developed for calculating this type of loss. This flux, if analyzed, will be found, in general, to contain many harmonics. In salient-pole

machines the third or fifth harmonics may be larger than the fundamental. The eddy losses in the copper conductors due to each harmonic may be calculated and the results added to give the total loss. (See Lamme for a discussion of this type of loss.[2]) These losses become appreciable, of course, only when the teeth begin to saturate.

2. *b*. The losses in metal wedges would be difficult to calculate, especially when wedges containing iron are used. This effect can be determined experimentally, however, for special types of wedges and slot dimensions. Band losses can be calculated approximately by methods which recently have been devised.[3]

2. *c*. When machines operate at fairly high flux densities, there are often a.-c. fluxes which leak into the solid end frames, coil supports, etc. While these densities may not be large, they may be responsible for considerable losses due to the fact that even low-flux densities will produce large hysteresis and eddy losses in solid masses. This effect is often chiefly responsible for the very rapid increase in losses which occurs in some machines as the voltage is increased above normal.

3. *a*. Tooth-frequency losses in the cores are due to the individual tooth high-frequency-flux pulsations penetrating a short distance into the core and to high-frequency fluxes which extend throughout the whole magnetic circuit due to pulsations of reluctance as the teeth pass the poles or opposing teeth. By choosing the proper tangential pole width with reference to the number of teeth, or by suitably chamfering the pole tips, this effect may be minimized in salient pole machines. Although these pulsations may be small in magnitude, if they pass through solid magnetic material, they may produce considerable losses due to their high frequency.

3. *b*. In rotating machines where both the stator and rotor are slotted, high-frequency-flux pulsations in the teeth of considerable magnitude may be produced. If the stator slots are open, even though the rotor slots are partly or nearly closed, very considerable hysteresis and eddy losses may occur in the rotor teeth. In some poorly designed commercial machines, these high-frequency tooth losses have been known to be two or three times the fundamental-frequency losses. They can be reduced by the use of partly closed slots or magnetic wedges. Also, if the rotor and stator slot pitches were equal, they would be negligible. Under these conditions, however, there would be excessive noise

and vibration. As a consequence the numbers of stator and rotor teeth are nearly always made somewhat different and a certain amount of pulsation loss results. These tooth pulsations produce minor hysteresis loops superposed on the major loop, as illustrated by Fig. 209. Various methods of calculating the magnitude of these pulsations have been devised, but they cannot be considered here.[4,5] As the teeth approach saturation, the magnitude of the pulsations decreases. If it were not for this effect, tooth-pulsation losses in induction motors and similar machines would be much greater than they are, when the tooth inductions are fairly high.

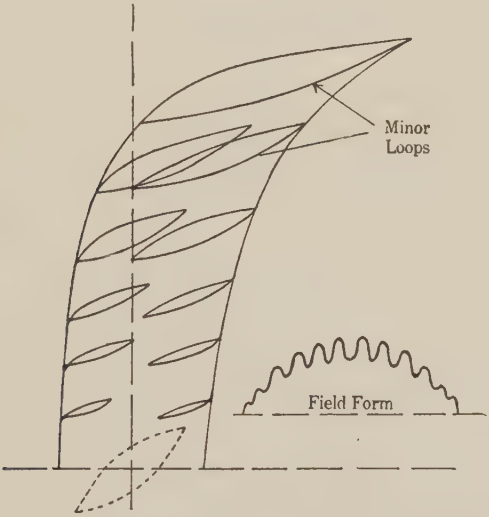

Fig. 209.—Hysteresis loops; sine-wave field form.

In the case of squirrel-cage-induction motors (even though without the cage windings there would be no appreciable pulsations in the stator teeth), the high-frequency circulating currents in the cage windings, which damp out the high-frequency-flux pulsations in the rotor teeth, may cause the pulsations to be reflected to the stator teeth and produce appreciable pulsation losses in the stator teeth.

The method of estimating these pulsation losses is somewhat complicated, but it is possible to calculate them in most cases with a fair degree of accuracy.

In the case of salient-pole machines, the rapid increase in tooth flux as the teeth pass under the pole tip may produce quite appreciably increased eddy losses over those which would exist for a sine-wave distribution of flux. These extra losses could be estimated from a knowledge of the harmonics in the field form.

4. Surface or pole-face losses exist both in salient-pole machines and in machines where both members are slotted. Due to the slots in the armature of a salient-pole machine, for instance, flux ripples travel along the surface of the pole and penetrate an appreciable distance below the surface. Since they are of tooth frequency, they often produce very considerable losses, especially in the case of small air-gaps and thick laminations or solid poles. If the poles have damper windings, the pole-face losses may be more than doubled. In this case they correspond closely to the conditions in an induction motor. These losses often amount to 10 or 20 per cent of the total core losses, and should not be neglected. In the case of turbo generators they may be quite large, since the rotors are of solid material. These turbo pole-face losses are reduced, however, due to the fact that turbo air-gaps are large.

For open-slot stators the surface losses in induction-motor rotors may be of considerable magnitude, due to the small air-gaps. These losses increase as some power between one and two of the ratio of the slot width to the air-gap. A further discussion of the subject of pole-face or surface losses will be found in the *Transactions* of the American Institute of Electrical Engineers.[6,7]

5. In the case of squirrel-cage-induction motors and salient-pole machines with damper windings, tooth pulsations, which would normally occur if the windings were not present, are largely damped out, but in their stead high-frequency circulating currents appear, sometimes of considerable magnitude, in the short-circuited windings. Since these currents are of high frequency, there may be considerable skin effect produced, thus increasing the effective resistance of the copper. These circulating currents may cause quite appreciable losses, but these losses, in general, will be much less than those which would have occurred in the teeth had the copper been absent.

6. If tooth pulsations are present and the tooth inductions become of sufficient magnitude to produce saturation, high-frequency leakage fluxes, both tangential and radial, will occur in the slots. Even though the fluxes are of only a few hundred

gausses in density, they may, due to their high frequency, cause quite appreciable eddy losses in the copper conductors, unless the conductors are well laminated. Often, the decrease in tooth-pulsation losses due to saturation will be more than compensated for by the copper eddy losses, the net result being a rapid increase in pulsation losses with induction.

7. The extra losses due to nonsinusoidal flux distribution would be difficult to estimate and for most machines would be comparatively small. In general they may be neglected.

B. Illegitimate Core Losses.—1. As pointed out in the discussion of transformer losses, if the laminations happen to be bent sufficiently to be permanently distorted before assembly, when the pressure is applied they will be straightened out with a resulting increase in hysteresis loss. This effect is small for proper methods of manufacture.

2. For small machines having narrow teeth, there may be a very considerable increase in tooth losses due to punching strains, provided the laminations are not annealed after punching. For instance, if a tooth has an average width of only 0.25 inch the hysteresis losses in the tooth will be increased approximately 50 per cent by the punching operation (see Chap. VIII). Small motors often have considerably narrower teeth than this.

3. It is not uncommon practice to file the slots of completed punching assemblies before introducing the windings. If the punchings are already short-circuited by being forced on the shaft or onto dove tails, this filing will complete an electrical circuit which may permit very considerable eddy-currents to flow, thus causing increased core losses. These increased losses are of quite large magnitude in some types of construction. Slot filing is bad practice, and should not be resorted to except in case of necessity, provided the laminations are already short-circuited on the opposite edge.

4. The cores of rotating machines are often placed under considerable pressure in the assembly operation. If the insulation on the laminations is poor, or if appreciable punching burrs are present, this pressure may produce short-circuited laminations, as in the case for slot filing, and the result will be increased losses due to eddy-currents. In the earlier days of electrical manufacture it was not at all uncommon to be able to increase the efficiency of a rotating machine by an appreciable amount simply by loosening the clamping bolts.

5. If, due to a rough surface, scale, poor insulation, or some other cause, the space or stacking factor is low, the required amount of iron cannot be placed in the core, with the result that, at a definite operating voltage for the machine, the core and tooth inductions will be abnormally high. Since permeability decreases rapidly with increasing induction at the operating flux densities of rotating machines, the result may be very considerably increased leakage fluxes above normal. If these leakage fluxes can penetrate solid masses of metallic material, such as end frames, unexpectedly large extra losses may result. This is a rather common cause of variation of loss in what are supposed to be duplicate machines which are built at different times. Often, too little care is exercised in the inspection of the surface of electrical sheet.

C. Stray Losses.—1. Due to armature reaction in salient-pole machines, the flux at the pole surface may become far from symmetrical as the load is increased. This means a decrease in flux under one pole tip and an increase under the other. Since pole-face, and copper eddy losses due to leakage flux increase as some power of the induction often much greater than one, the decrease in loss at one pole tip will be less than the increase at the other. The result may be considerably increased losses under load conditions in those types of loss which are normally considered to be independent of load. Lamme has given a very complete discussion of these effects.[2]

2. Due to the production of skin effects in the copper conductors, caused by the flux resulting from the load current, there is a tendency to force the current toward the portion of the windings in the tops of the slots. The result is an increase in the effective resistance of the conductors and therefore increased losses. This type of loss is beyond the scope of this discussion. It has been dealt with very ably by Field, Gilman, and others.

3. The end windings of rotating machines are often located close to the end frames, metallic supports, etc. For heavy-current machines, the load currents may produce sufficient leakage flux to cause very appreciable hysteresis and eddy losses in these solid materials. If the magnitude of the m.m.fs. is known, these losses may be calculated, approximately at least, by Rosenberg's formulas as given in Chap. VII. They may be reduced by the use of nonmagnetic materials, if it is not feasible to increase the distance between the conductors and the members in question.

If the solid material forms a parallel path to the leakage flux, the eddy losses may be decreased by decreasing the resistivity; if it forms a series path, the resistivity should be increased.

4. Under load conditions, for induction motors at least, it has been shown by Rogowski and Vieweg[8] that the tooth pulsations, even with totally closed slots in one member, may be very considerably increased by the m.m.f. produced by the load currents. According to the above-mentioned authorities, this effect is chiefly responsible for the stray losses in induction motors. These effects are difficult to calculate quantitatively, but certain empirical constants may be used for definite types of machines in order to allow for them.

Summary.—In most rotating machines there are extra no-load losses over those due directly to the fundamental-frequency flux in the teeth and core, which are often equal to or greater than the normal fundamental-frequency losses. In salient-pole machines these extra losses are due chiefly to pole-face or surface losses, eddy-currents in the cores due to short-circuited laminations, copper eddy-currents caused by slot-leakage fluxes, alternating leakage fluxes into the end frames; and, in small machines, to punching strains.

In induction motors and machines having both the stator and rotor slotted, these extra losses are due chiefly to surface and tooth-pulsation losses. For the higher induction machines, there may be considerable copper eddy losses in the rotor windings, even at no load. For the smaller machines the effect of punching may be considerable. In turbo-alternators the surface losses may be of extra large magnitude, due to the use of solid rotors.

Stray iron losses in salient-pole machines are chiefly due to concentration of flux under one edge of the pole shoes and to a.-c. leakage fluxes from the end windings. In induction motors stray losses are chiefly due to increased tooth-pulsation losses produced by the increased tooth m.m.fs.

All of these types of loss may be calculated approximately, but it is a long tedious process in many cases with the methods at present available. Unless a radically new design is under consideration, or the cause of extra high losses is being sought, iron losses can be best calculated from empirical constants obtained from tests on similar machines.

Hughes,[9] in England, has recently given an empirical formula for calculating the no-load core losses in d.-c. machines, which has the merit of simplicity and which, perhaps, can be used quite widely if suitable constants are determined for each given class of machine and kind of core material used. The core loss W, for 0.018 inch thick low-silicon sheet, is

$$W = K_1 f^{1 \cdot 5}(V_a B_a^2 + V_t B_t^2), \qquad (110)$$

where $K_1 = 3 \times 10^{-6}$ for B in kilolines per cm.^{2} and V in cm.^{3} (0.018 inch low silicon),

f is in cycles per second;

V is the volume.

The subscripts a and t refer to the armature and teeth, respectively.

In another form of the equation,

$$W = K_2 f^{1 \cdot 5}(W_a B_a^2 + W_t B_t^2), \qquad (111)$$

where W_a and W_t are the weights of the armature core and tooth material in pounds, and B is as before, $K_2 = 58.2K_1$.
This corresponds to an iron loss per pound at 50 cycles and 10 kilogausses of 6.18 watts. An Epstein test on the same material gives about 1.55 according to the suppliers.

These K factors are higher than are commonly found for high-grade American machines. Much of the difference between 6.18 and 1.55 is probably due to illegitimate losses, but some of it, of course, is due to pole-face and other extra losses.

Such formulas as the above, of course, are altogether too general for any but standard types of machines operating over a limited range of inductions, but should be very useful if properly applied.

1. Induction Motor Core Losses, P. L. ALGER and R. EKSERGIAN, *Jour. A.I.E.E.*, vol. 39, p. 906, October, 1920.

2. Iron Losses in Direct-current Machines, B. G. LAMME, *Electrical Eng. Papers*, p. 483.

3. Motor Band Losses, THOMAS SPOONER, *Jour. A.I.E.E.*, p. 14, January, 1926.

4. Tooth Pulsations in Rotating Machines, Thomas SPOONER, *Trans. A.I.E.E.*, p. 252, 1924.

5. Tooth-frequency Iron Losses in Slip-ring Induction Motors, D. B. HOSEASON, *Electrician*, Sept. 7, 1923.

6. ADAMS, LANIER, POPE and SCHOOLEY, *Trans. A.I.E.E.*, p. 1133,1909.

7. SPOONER and KINNARD, *Trans. A.I.E.E.*, p. 262, 1924.

8. Load Losses in Small Three-phase Induction Motors, W. ROGOWSKI and V. VIEWEG, *Archiv. fur Elektrotechnik*, vol. 14, p. 524, July 7, 1925.

9. Iron Losses in D.-c. Machines, E. HUGHES, *Jour. I.E.E.*, vol. 63, p. 35, December, 1924.

CHAPTER XXV

MAGNETIC ANALYSIS

If the average electrical engineer or physicist were asked for a definition of magnetic analysis, he probably would be unable to give an adequate one; or if the same question were asked of various magnetic experts, each would probably give a different definition. There are two reasons for this; first, magnetic analysis is a very young infant and, like the infant, its chief present value lies in its possibilities; second, magnetic analysis has various branches, just as has chemical analysis.

It has been known for many years that there are certain relations between the magnetic and other physical properties of magnetic materials. It also has been recognized that chemical composition has an important and often profound influence on the magnetic properties of iron and other ferromagnetic materials. Again, temperature bears a most important relation to magnetic properties. This applies both to the magnetic properties of the material for a given temperature and to its magnetic properties as influenced by its previous thermal history.

There are many magnetic measurements which can be made quickly and simply on specimens, which in no way injure the material. Obviously then, if some definite relation can be established between a magnetic property or properties and the physical properties, state or composition of a material concerning which information is required, an extremely simple and valuable tool is at hand.

Some years ago Dr. C. W. Burrows and his associates, while at the Bureau of Standards, did some valuable pioneer work along this line in an endeavor to establish the possibilities of magnetic analysis for commercial applications. Doctor Burrows' results indicated that for a given physical state, the ferromagnetic properties of a material are unique. A number of investigators in this and other countries have since made many commercial applications of this principle.*

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* A very complete discussion of this subject is given by the "Topical Discussion on Magnetic Analysis" presented before the American Society

It will be the endeavor here to show what has been accomplished along this line and to indicate some of the methods and possibilities of magnetic analysis. It must be emphasized, however, that the art is in its infancy and its ultimate possibilities can be only guessed.

Types of Magnetic Analysis.—As first developed by Doctor Burrows and his collaborators, magnetic analysis was applied chiefly for the determination of cracks, flaws, or inhomogeneities in specimens of magnetic material by moving an exploring coil connected to a detector (fluxmeter or galvanometer) with reference to the sample. When a flaw is passed, the magnetic-flux leakage cuts the coil and induces an e.m.f. which can be measured.

Doctor Burrows, F. P. Fahy, R. L. Sanford, A. V. deForest, and others also have developed magnetic analysis to determine, by means of magnetic tests, the constitutional state of a steel resulting from certain heat-treatments and from chemical composition. Austenite, martensite, troostite, sorbite, pearlite, and ferrite all have different magnetic characteristics, and by the measurement of one or more of these magnetic characteristics, the average state may be more or less accurately determined.

Honda and his associates in Japan use magnetic analysis to follow the structural changes in carbon and alloy steels as they are heated and cooled, thus obtaining a knowledge of the constituents of the steel as affected by temperature and giving a ready means of accurate temperature control.

Fraichet in France employs magnetic analysis chiefly as a means of studying the effect of stress on iron and steel. This is a very sensitive method, since the magnetic properties of iron and steel are greatly altered by strain.

In England Crapper uses the term magnetic analysis to designate simply a study of the normal-temperature magnetic properties of ferromagnetic materials as affected by composition and heat-treatment. This is contrary to the common usage in this country, however, since in general the term magnetic analysis

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for Testing Materials, June, 1919. Also Doctor Burrows has given a good presentation of the subject in *Bur. Standards Sci. Paper*, 272, on "Correlation of Magnetic Properties and Mechanical Properties of Steel." We are greatly indebted to these two sources for much of the information in this chapter. Sanford's article, in *Trans. A.S.S.T.* for June 1924, presents a good summary of the present state of the art. The bibliography attached to that paper is particularly complete.

is used to indicate the process of determining other physical properties of a material from a knowledge of the magnetic properties.

It is evident that these various types of magnetic analysis should assist more or less successfully in determining the presence of cracks, flaws, and inhomogeneities in ferromagnetic materials, in obtaining certain evidence concerning the chemical composition, in determining whether or not the material has been properly heat-treated, in ascertaining the state of internal strains due to heat-treatment or mechanical working, in following structural changes due to temperature cycles and thereby accurately controlling the temperature cycles, and in doing all these things quickly, more or less independent of the size and shape of the specimen and without destroying it, or leaving any mark on the material.

If all of these things could be done successfully, magnetic analysis would be an extremely valuable tool and would be in demand for many purposes. Unfortunately, the problem is not as simple as it seems at first. The technique of magnetic measurements is usually comparatively simple, with several means available for making practically the same measurements. The difficulty is in properly interpreting the results and segregating the various factors. For instance, suppose it is desired to determine by magnetic means the internal structure of a heat-treated carbon steel in order to be able to predict its tensile strength. Near the surface there may be martensite; further in, troostite; and still further in, sorbite. Each has its own magnetic characteristics, but in general all that will be measured magnetically, except under very special conditions, is a mean value. Again, unless a specimen of magnetic material has been thoroughly annealed, it contains internal stresses which may alter the magnetic properties. To differentiate between the effects of strain and constitution is difficult. If, however, a specimen of a given size, shape, and chemical composition is available, and can be properly heat-treated, magnetic analysis furnishes a means of determining whether or not all other similar specimens have received the same treatment and are of the same chemical composition.

Magnetic Criteria.—Consider briefly some of the magnetic properties which are available for the uses of magnetic analysis. Figure 2* is an ordinary magnetization or *B-H* curve for a magnetic material. It gives the relation between the magnetic flux or induction B and the magnetizing force H which produces the flux. If desired, H may be expressed in terms of the current in a coil surrounding the specimen which is being investigated. The permeability or μ-H curve, also shown in Fig. 2, may be derived from the magnetization curve by the relation $\mu = B/H$. The maximum permeability μ_m corresponds, of course, to the point of tangency on the magnetization curve of the straight line through the origin, as indicated. Various portions of the magnetization or permeability curve are useful for different purposes, as will be discussed in greater detail later. The initial permeability μ_o is the permeability at zero H. The differential permeability μ_d for any point on the magnetization curve is given by the slope of the curve at that point or is equal to $\frac{dB}{dH}$. The maximum differential permeability occurs, of course, at the point of inflection of the magnetization curve.

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* Chap. II, p. 7.

If $\frac{H}{B}$ or $\frac{H}{B - H}$ be plotted against H, a curve is obtained as in Fig. 4,* called the reluctivity curve. Above 200 or 300 gilberts per centimeter, this curve is usually a straight line. If it is not, any bends in the curve have a special significance for magnetic analysis which will be discussed later. This straight portion may be expressed by the formula $\frac{H}{B} = \nu = \alpha + \sigma H$, where α is given by the intercept on the vertical axis, and σ is the slope of the line. For high inductions, it is necessary to use $\frac{H}{B - H}$ instead of $\frac{H}{B}$. The reciprocal of the slope $\frac{1}{\sigma}$ is the saturation induction of a material. The intercept α is sometimes used as a measure of the hardness of a material, since it is in general proportional to the hardness. It is called the coefficient of magnetic hardness.

In addition to the magnetization, permeability, and reluctivity curves, the hysteresis loop has many useful properties. Referring to Fig. 210, the maximum induction B_m and the corresponding H_m are, of course, the coordinates of a point on the magnetization curve. The retentivity B_r is the residual induction remaining after H_m is reduced to zero. H_c, the coercive force, is the reversed magnetizing force necessary to reduce B_m to zero. The area of the loop is proportional to the hysteresis loss.

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* Chap. II, p. 12.

If the magnetizing force is reduced from H_m to H_a, the induction will drop from B_m to a. If it is increased to H_m again, the induction will return approximately to B_m by another path, tracing the small minor loop as indicated. Similarly, the loops B_rb, H_cc, and de may be traced. If the change ΔB in B is divided by the change ΔH in H, an effective permeability μ_Δ called the incremental permeability[1] is obtained. This incremental permeability is proportional to the slope of the line drawn between the tips of the minor loop. When H is reduced to zero from the point H_c the induction goes to a point c. Fahy calls the induction Oc, the elastic induction.

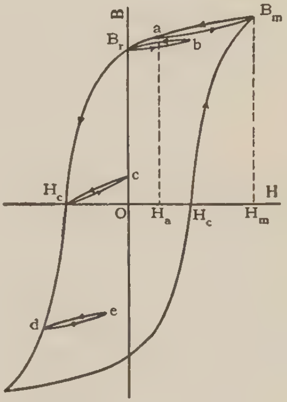

FIG. 210.—Hysteresis loop.

The properties of the magnetization curve and the hysteresis loop may be called the d.-c. characteristics of a material. These d.-c. characteristics give, then, the following quantities which may be used for magnetic analysis:

1. Permeability (μ):
   - *a.* μ for any given induction.
   - *b.* μ for any given magnetizing force.
   - *c.* μ_o (initial permeability).
   - *d.* μ_m (maximum permeability).
   - *e.* μ_d (differential permeability).
   - *f.* μ_Δ (incremental permeability).
2. B for any value of H on the magnetization curve (corresponds to 1*b*).
3. H for any value of B on the magnetization curve (corresponds to 1*a*).
4. The reluctivity relationship (see Fig. 4).
5. Retentivity B_r for any value of B_m or H_m.
6. Coercive force H_c for any value of B_m or H_m.
7. Hysteresis loss (area of hysteresis loop).
8. Elastic induction (see 1*f*).

9. Some combination of the above, such as $B_m \times H_c$, B_r/B_m, etc.

When a.c. is applied to a specimen, a whole new line of possibilities is opened up. In addition to the hysteresis loss, there is the eddy-current loss which is largely a function of the resistivity of a material (for a given size and shape of specimen). Referring to Fig. 211, suppose a sample is surrounded by two windings consisting of a primary and a secondary. If an alternating voltage E_p is applied to the primary winding, a flux ϕ will be produced which in turn produces an induced voltage E_s' in the secondary 90 degrees behind it. The corresponding primary voltage is E_p'. The primary current is I_p. This may be divided into two components, one parallel to ϕ which is the magnetizing component I_m and is a function of the effective permeability of the material; the other I_w which is the loss component and is proportional to the hysteresis and eddy losses in the specimen. Now, if by some means I_m is determined, there is a measure of the permeability. If we measure I_w, there is a measure of the losses.

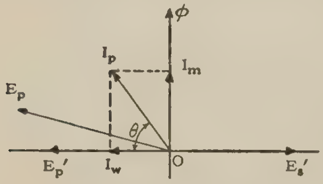

Fig. 211.—Vector diagram for a.-c. tests on specimen with two windings.

If, instead of applying a definite voltage, a certain current is applied to the primary winding surrounding the sample, two components of the voltage on the secondary winding may be measured there, which will be proportional to permeability and losses, respectively, or to any desired combination of the two.

By changing the frequency, loss results may be obtained which are largely a function of the hysteresis for low frequencies or of the eddy losses or resistance for high frequencies. By making a test at two or more frequencies, it is possible to separate the hysteresis and eddy losses.

By the use of a bridge arrangement, several of which have been successfully developed by A. V. deForest, it is possible to obtain very high sensitivity and thus make possible the measurement of small magnetic changes. These a.-c. methods will be made clearer later by a specific example.

Specific Applications. *Leakage Method.*—The leakage method of test makes use of the property of permeability and depends upon a sudden change of effective permeability, as shown by Fig.

212. Suppose a magnetic bar *A* is uniformly magnetized longitudinally, and a coil *B*, surrounding the bar and connected to a galvanometer *G*, is moved along the bar in the direction indicated. No deflection will be shown on the galvanometer provided the flux in the bar is uniform. If, however, a flaw such as a crack or slag inclusion exists at *C*, the flux will leak out around this flaw, since the effective cross-section of the magnetic path is restricted. When the coil *B* cuts these leakage lines, the galvanometer *G* will deflect, thus indicating a flaw. The method depends, then, upon a nonuniform material and a relative motion between a test coil and the material. It is obvious that many modifications of this method are possible and it is also obvious that either the coil or the material may move. Also, the test coil does not need to surround the specimen, but may simply lie close to it. Again, there may be two coils differentially connected.

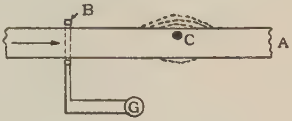

FIG. 212.—Flux-leakage method of testing. Using a movable coil and galvanometer.

One of Burrows' early applications of this method was to the testing of steel rails. Most types of flaws, except, perhaps, longitudinal cracks or seams, could be detected. The difficulty with the method is that comparatively harmless physical strains caused by straightening the rails in the process of manufacture, strains introduced in service caused by the method of supporting the rails on ties, etc. often produce magnetic indications which are far in excess of those caused by real flaws. This constitutes the chief difficulty in successfully applying this method of analysis.

This type of magnetic analysis has been applied more or less successfully to the inspection of turbine-rotor discs, rifle-barrel stock, helical springs, elevator cables, and other finished and unfinished products. Doctor Burrows' defectoscopes operate on this principle.

To summarize, while the leakage method will indicate many types of flaws, it also gives indications of the same magnitude for effects which are not of particular importance and this greatly limits its usefulness.

Before leaving the leakage method, it should be mentioned that a somewhat different type of test which was devised by Hoke,* also depends upon magnetic leakage. If a specimen of iron or steel is magnetized and then placed in an oil bath containing finely divided iron particles, these particles will collect on the specimen wherever there is any appreciable flux leakage. If surface cracks are present, they will be plainly shown by deposits of the iron particles. Figure 213 illustrates such deposits as shown by the white lines. The specimen was a heat treated steel block ground after quenching. Cracks which are nearly, if not quite, invisible to the naked eye are readily revealed by this method.

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* United States patent No. 1426384.

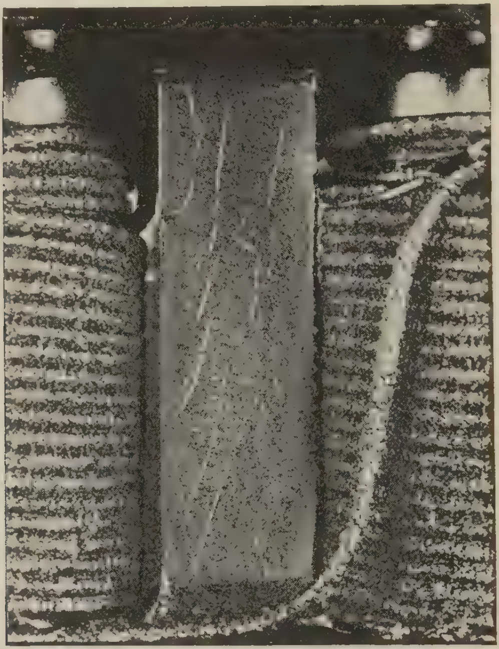

FIG. 213.—Another test using the flux-leakage principle.

Showing the magnetized sample after removal from an oil bath containing finely divided iron.

It is possible also to obtain deposits over cracks which are $\frac{1}{8}$ inch or more below the surface if the conditions are favorable. For soft specimens, the magnetizing field should be applied during the time that the material is in the bath and afterwards until the inspection is completed. If the material is fairly hard magnetically, the residual magnetism is sufficient to hold the iron particles. This method has been successfully used by the Metropolitan-Vickers Company and others for the detection of surface cracks in heat-treated gears and pinions.

Determination of Physical Properties.—As a specific example of this application, consider the relation between mechanical hardness and magnetic properties. It has been found by experiment that, of the various magnetic properties available, the coercive force H_c lines up very well in general with the hardness. Figure 214 shows some results reported by Nusbaum,[2] which are typical. If the hardness had been varied by other means than tempering, there still would be a similar relation, but it perhaps would have been somewhat different, quantitatively.

Gebert[3] has shown some very striking relations between hysteresis and the mechanical properties, hardness and tensile strength, by plotting Brinell hardness and tensile strength against the product of the maximum induction and coercive force ($B_m \times H_c$). This product is approximately proportional to the area of the hysteresis loop or hysteresis loss. Figures 215 and 216 illustrate the results. Instead of measuring B_m and H_c ballistically, by means of a permeameter as Gebert did, if desired, the hysteresis loss may be measured by means of a simple a.-c. test.

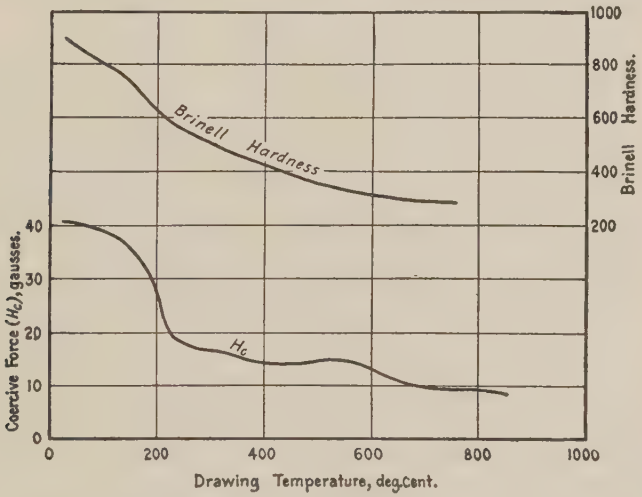

FIG. 214.—Effect of heat-treatment on coercive force and hardness of a manganese steel.

These relations, however, have to be used with caution. The hardness and tensile strength may be accompanied by an increase in H_c or hysteresis for certain materials and certain treatments for a certain range and then for another range, the mechanical properties may increase and the magnetic properties decrease. It is necessary to consider each material with its specific treatment by itself, as in the present state of the art no reliable predictions can be made by analogy.

Effect of Heat-treatment.—Intimately connected with the relation between mechanical properties and magnetic properties is the subject of heat-treatment. The magnetic properties of a material are often greatly affected by heat-treatment, the changes in temperature acting in three ways:

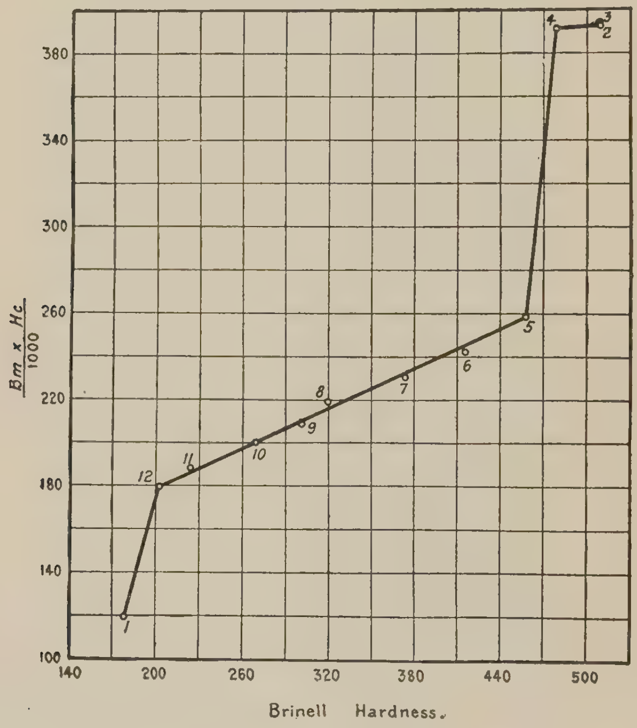

FIG. 215.—Relation of hysteresis area and Brinell hardness for a nickel steel.

1. A quench produces mechanical strains in the material which in general lower the magnetic quality by causing a decrease in permeability and an increase in H_c and the hysteresis losses. A draw or anneal will remove these strains, thus improving the magnetic quality. A cold-worked material may also contain

strains which are removable by annealing with a corresponding change in magnetic properties.

2. A quench in the case of carbon or alloy steels, if from a sufficiently high temperature, will leave the material in a different state from the normalized condition (namely, austenitic, martensitic, sorbitic, etc.). Each change of state is accompanied by more or less definite magnetic changes, as will be pointed out in detail later. A draw or anneal in general will change the state and produce magnetic changes as well as relieve strains.

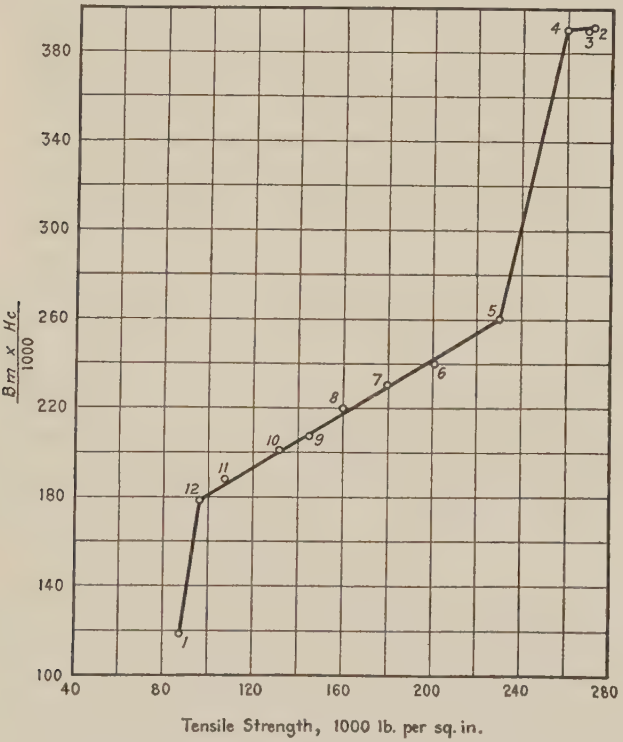

FIG. 216.—Relation of hysteresis area and tensile strength for a nickel steel.

3. If the temperatures are sufficiently high and the atmosphere is not a vacuum or neutral gas, the material may be oxidized, carbonized, or decarbonized, with resulting magnetic changes.

In Fig. 217, Burrows shows the effect of quenching on the normal induction of a 1 per cent carbon steel. The circles at the left of zero H give the B_r values according to the vertical scale;

the corresponding H_c values are given by the horizontal scale. It will be noted that a quench reduces the induction values for a given H and increases the H_c, and that a water quench is much more drastic than an oil quench. Figure 217 also shows the effect of drawing on this same material after a water quench. It may be noted that the high-induction permeability and B_r reach a maximum for intermediate drawing temperatures, but decrease for high drawing temperatures; whereas, the maximum permeability μ_m continues to increase with drawing temperature, except at the highest points where oxidation was probably present. The H_c values decrease steadily with drawing temperature. Evidently, then, a magnetic test is capable of yielding quite reliable data as to previous heat-treatment for a carbon steel. Alloy steels give similar results, although the magnitude is different. From a knowledge of the effect of heat-treatment on the constitutional state, and a knowledge of the various magnetic properties of the various states, these magnetic results due to heat-treatment may be readily explained.

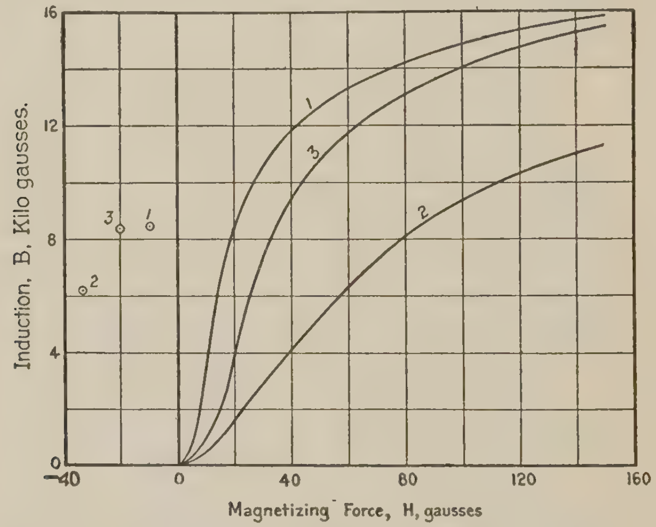

FIG. 217.—Normal induction and hysteresis data for carbon steel.
1. As received. 2. Quenched in water from above the critical point. 3. Quenched in oil from above the critical point.

For instance, austenite (obtained by rapid quenching of certain steels) is in general nonmagnetic. Martensite (next stage) has a higher saturation induction and H_c, but its maximum permeability is not very high. Pearlite is a soft material resulting from annealing and has a somewhat less saturation induction than martensite, a low H_c, and a high-maximum permeability.

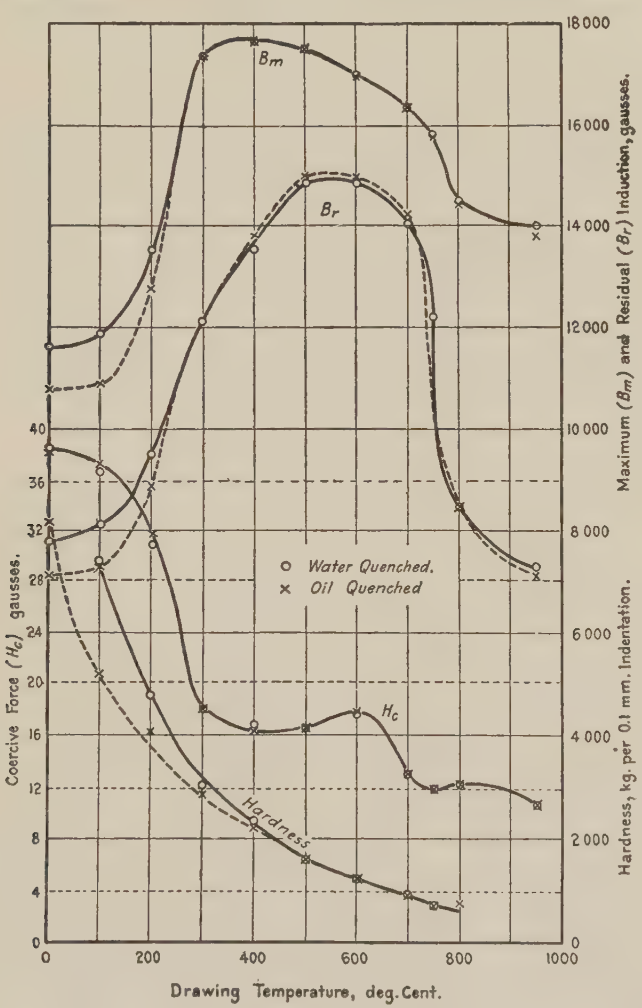

FIG. 218.—Effect of heat-treatment on magnetic properties and mechanical hardness of an alloy steel.

Sorbite and troostite have intermediate values. These effects are illustrated by Fig. 218, due to Nusbaum, for an alloy steel. As the drawing temperature increases, the material changes to martensite, troostite, sorbite, and, finally, pearlite, with the magnetic changes as indicated. As pointed out by Nusbaum, it may not be possible to determine the constitutional state of a material from a single magnetic property, but by properly combining two or more of them, the prediction is much more reliable. Many data are available along this line, but space does not permit further consideration of the details.

A particularly useful method of determining whether or not material consists of two or more constituents is the reluctivity relationship,[4] Fig. 4. If a sample consists of two constituents, one of which is much more easily magnetizable than the other (consider the case of a quenched steel, for instance), the flux first will be carried almost entirely by the higher permeability material. At the higher magnetizing forces, however, the flux will start to penetrate the lower permeability material, giving the effect of an increase in cross-section. This condition is marked by a more or less sudden bend in the reluctivity curve, and this furnishes a means of detecting the condition of nonhomogeneity.

As will be pointed out presently, stresses as well as structural differences are responsible for magnetic inhomogeneity indications. The reluctivity relations will then often indicate conditions of internal stress.

The shape of the hysteresis loop will also sometimes indicate the presence of two or more constituents. If there is a high and a low coercive-force material both present in a specimen, the loop often will be wide at the top and narrow near zero apparent induction for obvious reasons. The induction is not really at zero, but one portion is considerably negative and the other considerably positive, the actual values depending on the relative cross-sections of the two constituents.

Chemical Composition.—It often happens that stocks of material become mixed or that a quick test for the percentage of a certain element in a heat of steel is desired. A simple test by a d.-c. or an a.-c. method for permeability, coercive force, or hysteresis loss will in general readily distinguish between carbon steels of different percentages or between carbon and alloy steels. It is usually a simple matter to select some magnetic property which is most suitable for the particular application.

An interesting device called a carbometer[5] recently has been developed in Sweden for determining the carbon percentage in a steel-furnace melt before tapping the heat. This depends for its operation upon the measurement of the incremental permeability by means of a very special permeameter. The sample is a small cylindrical casting. The process of casting the test sample and

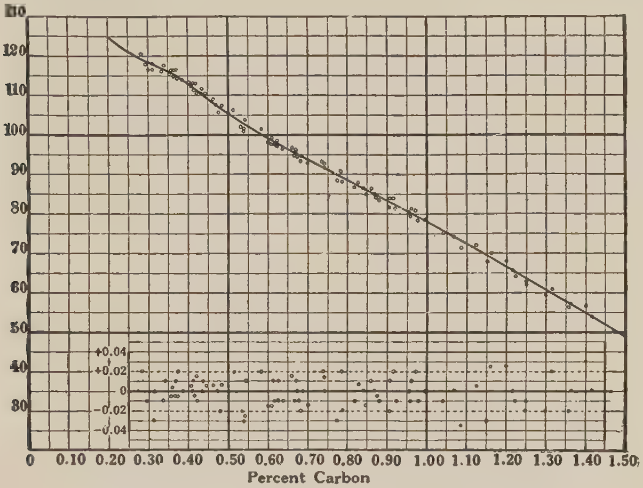

FIG. 219.—Carbometer carbon curve and chemical analyses of hardened specimens.

The difference between the results by carbometer and by chemical analysis is shown at the bottom of the diagram to enlarged scale.

testing requires only 1.5 minutes for material above 0.35 per cent carbon, and 3.5 minutes for material with a lower carbon content. Figures 219 and 220 give test values for a series of samples. For the higher carbon percentages, the samples are quenched in water and for the lower per centages, the samples are somewhat cooled before quenching. The ordinates of the curves are proportional to the induction range for a change of magnetizing force from the maximum used to a smaller value of the same sign. What is measured then is the incremental permeability. The results seem to be as accurate and reliable as could be obtained by ordinary chemical analysis and the required time is much less, which is of great importance in connection with open-hearth furnace manipulation. By applying suitable correction factors to the calibration curves, the apparatus may be used for alloy steels.

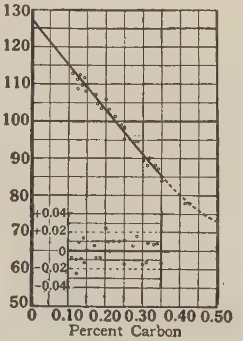

FIG. 220.—Carbometer carbon curve and chemical analyses of unhardened specimens.

Internal Strains.—When a magnetic material is stressed, the magnetic properties undergo a change. Figures 221 and 222 illustrate the effect of tension and compression on wrought iron.[6] It will be noted that, for compression, the greater the stress the lower the permeability; whereas, for tension, the permeability is increased for low, and decreased for high magnetizing forces. (The point at which the stress and no-load curves cross is called the Villari reversal point and is a function of the stress.) The magnetic properties of nickel, cobalt, etc. are affected differently by stress, but the relations are definite. Since, for iron, the effect of compression on the magnetic properties in general is much greater than the effect of tension, if a material is put under a bending strain, there will be a decrease in permeability and an increase in hysteresis loss or coercive force.

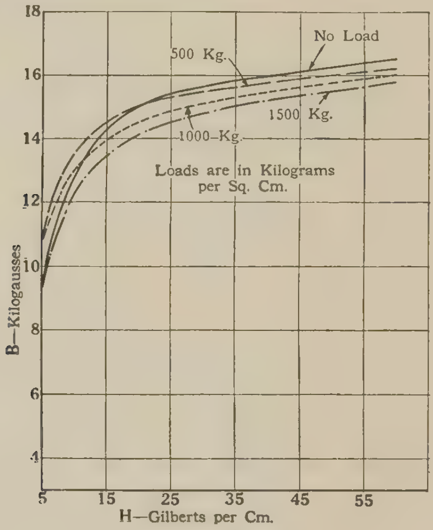

FIG. 221.—Effect of tension on the magnetization characteristic of wrought iron.

According to Fraichet,[7] the magnetic effects of stresses beyond the yield point are much smaller than for stresses below the elastic limit. A material which has been permanently strained, however, may show large magnetic changes due to the fact that certain portions are left in the stressed condition. In his work Fraichet simply applied a certain d.-c. magnetizing force to his sample by means of a primary winding, and then connected a secondary winding surrounding the sample to a galvanometer.

The deflections of the galvanometer were proportional to the rate of change of flux as caused by the effects of tension or compression.

Effects of stress readily may be obtained in another way by applying an a.-c. magnetizing force to a specimen and observing the change in reading of a voltmeter or a.-c. galvanometer connected to a secondary winding surrounding the sample. If desired, by suitable bridge arrangements, such as have been devised by deForest,[8] induced-voltage components may be measured which are proportional to the permeability, losses, or some combination. It is sometimes possible to obtain a component which gives nearly a straight-line relation against stress over a considerable range. Many applications of stress relations will suggest themselves. The connection between internal strains and heat-treatment already has been mentioned.

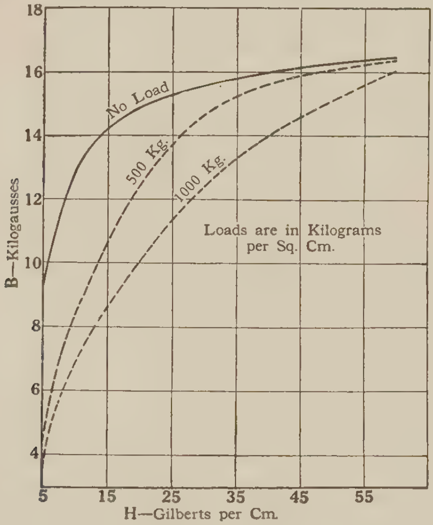

Fig. 222.—Effect of compression on the magnetization characteristic of wrought iron.

Temperature-magnetic Relations.—In Japan thermomagnetic analysis has been used chiefly in connection with the study of the changes which go on in magnetic specimens as the temperature is raised or lowered. Honda, particularly, has used the method very successfully in studying structural changes due to temperature variations. For instance, Fig. 223[9] shows typical cooling curves as obtained by a magnetometer for a 0.4 per cent carbon steel where the ordinates are proportional to the induction or permeability. The curves 1 and 2 are displaced upward 10 and 5 centimeters, respectively, from the zero position for clearness. The first rise in induction between 700 and 800°C. corresponds to the A_{r2} point* and is the point at which the material becomes magnetic. The bend at the A_{r1} point corresponds to the formation of pearlite. The bend at A_{r0} corresponds to the temperature at which cementite becomes magnetic. These curves are practically independent of the maximum temperature

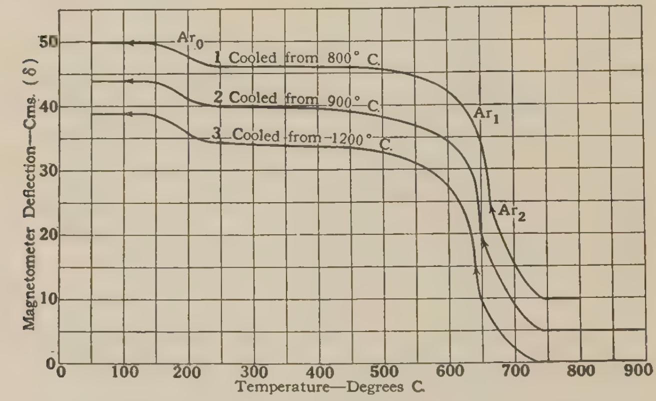

FIG. 223.—Thermomagnetic analysis of forged carbon steel. Composition: 0.80 per cent silicon, 0.41 per cent carbon.

* When a specimen of iron or steel is cooled and the rate of cooling is noted by means of a thermocouple or other temperature indicator, there are certain pauses or retardations in this rate of cooling at definite temperatures (for a given rate of cooling). These are called critical points and are accompanied by changes in the magnetic properties of the material. If these points are determined from the cooling curves they are called A_r points and if from heating curves A_c points. The A_r and A_c points for a given transformation are usually separated by a greater or less interval, depending on the rate of temperature change. With sufficiently slow rates they should coincide. The A_{r4} point corresponds to the temperature on cooling at which the iron structure changes from the body-centered cubic structure to the face-centered. At the A_{r3} point the structure changes back to the body-centered form accompanied by the separation of free ferrite (pure iron). There is no allotropic change at the A_{r2} point but iron changes here from a slightly magnetic to a strongly magnetic material. Pearlite, which is formed at the A_{r1} point, has a structure consisting of alternate layers of ferrite and cementite (Fe_3C). At the A_{r0} point whatever cementite is present becomes magnetic. This last point can be detected only by magnetic means.

for this particular material and are about the same as obtained with ordinary carbon steel containing no silicon. As the silicon or carbon content increases, these transformations occur at other temperatures or disappear, and new transformations appear. For instance, when the silicon content is sufficiently high, the A_{r0} point no longer appears, since cementite is prevented from forming by the silicon. As shown by Honda, the formation or decomposition of various silicides, etc. may be shown by magnetic means.

By a magnetic study of the cooling and heating curves of a steel, it is possible to estimate quite accurately the structure, if the experimenter is sufficiently experienced. By observing magnetically changes in the material, moreover, the proper time for quenching or the point at which to cease drawing may be accurately determined. A few commercial applications for quenching purposes, making use of the A_2 point, have been made, but the methods in general have not begun to be developed to the limits of their possibilities.

Another possible use of the magnetic transformations with temperature is a quick determination of certain chemical constituents of a material. For a given carbon content, for instance, one of the magnetic transformations would indicate approximately the percentage of silicon or some other alloying element, or for a given silicon content the carbon content could be determined by the temperature of the A_1 transformation.

Conclusions.—An attempt has been made to show some of the possibilities and present limitations of magnetic analysis. An outline of the various types of magnetic analysis, together with specific applications illustrating these various methods, has been presented. Detailed descriptions of specific methods have been beyond the scope of this book and would perhaps be of doubtful value, because each new problem should be considered by itself. There are so many possible solutions, and the relation between magnetic and other properties is often so complicated by a multiplicity of factors, such as simultaneous variations in chemical compositions, heat-treatment, mechanical strains, flaws, etc., that only an expert should undertake to solve a problem in magnetic analysis.

Obviously, in order that the magnetic laws and relationships underlying magnetic analysis shall be thoroughly known, much more experimental work is essential. It is the chief object of this chapter to stimulate interest along this line in order that these fundamental and necessary data may be more quickly forthcoming.

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